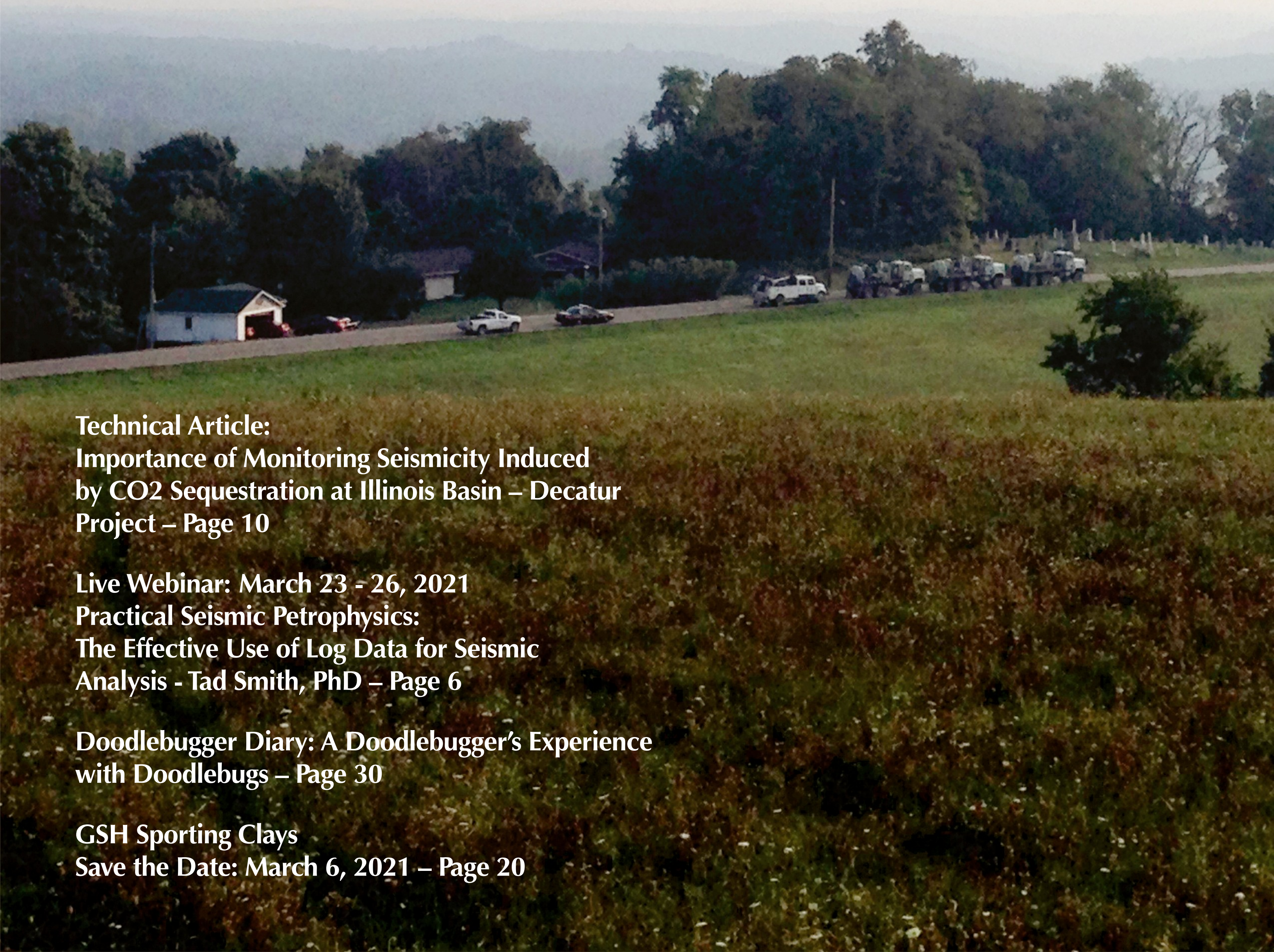
March 2021

# GSH Journal

GEOPHYSICAL SOCIETY OF HOUSTON
Volume 11 • Number 7

The Epicenter of
Geophysical Excellence



**Technical Article:**
**Importance of Monitoring Seismicity Induced by CO2 Sequestration at Illinois Basin – Decatur Project – Page 10**

**Live Webinar: March 23 - 26, 2021**
**Practical Seismic Petrophysics:**
**The Effective Use of Log Data for Seismic Analysis - Tad Smith, PhD – Page 6**

**Doodlebugger Diary: A Doodlebugger's Experience with Doodlebugs – Page 30**

**GSH Sporting Clays**
**Save the Date: March 6, 2021 – Page 20**

# TABLE of CONTENTS

**MEETINGS**



**FEATURES**



**CHECK THIS OUT**



**LOOK INSIDE**



***On The Cover.***

*Vibrators performing a 3D seismic survey in Utica.*

*Photo courtesy of Global Geophysical.*

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To ensure your information reaches the GSH members in a timely manner, please note the following deadlines and plan accordingly. Please submit your articles and any questions to Alvaro Chaveste, editor, at AlvaroChaveste@hotmail.com

**GSH JOURNAL DEADLINES**

| | |
|---|---|
| May 2021 | Mar 15 |
| Jun 2021 | Apr 12 |
| Sept 2021 | Jul 13 |

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# A Word from the Board

*By Marianne Rauch, First Vice President Elect*

I'd like to start off wishing all of you and your families a much improved 2021! Last year has been difficult and challenging in many ways for all of us. We were reminded that with all the progress humanity has made since the last worldwide pandemic at the beginning of the 20th century, we are no better in dealing with this, as we were then. Our daily lives came to a crashing halt, and with this came a collapse in oil and gas as the demand substantially declined. Not only did and still do we worry about the health of our loved ones and ourselves, but we must also deal with the financial consequences. Many of the members of our professional community have lost their jobs without much hope of finding another one. Businesses are closing daily, and we all wonder if our world and life will ever go back to what it was in the beginning of last year when all looked good.

In the middle of all this darkness, I found it amazing how compassionate, adaptable, and innovative we humans are! Presentations and whole conventions such as the URTeC and SEG were moved online with relatively short time to prepare. Although, I missed the personal interaction and seeing all my peers in person, I thought the online events worked well. There were even some advantages like being able to view presentations without having to leave the room and find the other venue! Then, the talks were recorded and made available for a certain amount of time to everyone who registered. In these cash strapped times, the reduced cost of attending such a convention should not be overlooked. Employers did not have to pay for travel, accommodation, etc. which would normally be the case. Hopefully, that allowed more people to attend and take advantage of the rich scientific offerings and idea exchanges that define such events. Optimistically, we will be able to have hybrid conventions that provide us with the best of both worlds, live and online events. The GSH followed this trend, and we moved all technical presentations online. Besides the obvious safety aspect, the main advantage of this is that we are not restricted to finding speakers within Houston, but we can recruit them from around the world. In addition, members who do not live here, can attend without having to travel. I am always excited when I see one of our out-of-town members listening to such technical presentations, as it means that our presence extends beyond Houston.

The one big question that we all ask ourselves is: what will this year bring? Will we have a miraculous recovery like we have seen in the past, slow recovery or will we stay stagnant? I am not an analyst and not in a position to make an official prediction but, I would say that we will have a slow recovery and that most likely, we will never go back to times with high oil and gas prices. Renewable energy sources will eventually replace most of the hydrocarbons, and less and less exploration will be performed with fewer wells drilled. I believe that it is essential that we adapt with the times and adjust the usage of geophysics. Let's look at where it can be most impactful. Geothermal comes to mind and so does $CO_2$ sequestration. Additionally, mapping storage for nuclear waste and solving near surface issues to allow building on safe sites would be good starting points. There will be more applications, but we need to take the lead and show the world that we are not dinosaurs that are at the brink of extinction! Our community must put on its thinking hat, be innovative and take risks (as geoscientists naturally do), only then will we have a meaningful role in society for a long time to come! And in the meantime, do not forget to support the GSH, so that we will continue to be able to offer excellent technical information and a local community. ◻

# From the Other Side

*By Lee Lawyer*

You may know how long I have been regaling you with this column. I started shortly after I retired from Chevron. That is well over 25 years ago. That does not seem so long, but the start of my profession was almost 40 years earlier. The early days were interesting from a geophysical point of view, as well as from a personal perspective. I received five offers of employment at the close of my college and military lives. I knew nothing about the petroleum industry, absolutely nothing. Why I chose to go with Standard Oil Company of Texas I can't recall. It's possible I used the flip of a coin to decide.

I was told to report to the main office of SOTEX (Chevron) located in Houston. My family consisted of wife and a very young baby, both of which I stashed in a motel somewhere on South Main while I checked in. The office was downtown, which made parking a problem. I reported to the Chief Geophysicist of SOTEX and was given a short lecture on what happens next. I was to journey to West Columbia, Texas, which is a small town just west of Angleton. There is an East Columbia, Texas but no town named Columbia!

At that time, we had five Chevron Seis crews operating in SOTEX. I reported to Party #5. We had a strange organization in those days. SOTEX was a wholly owned subsidiary of Standard Oil Company of California, which would later evolve into Chevron. SOTEX had a separate company for geophysics. At that time, we didn't let geophysics contaminate Districts, which were supervised by geologists. When I say I reported to a Seismic Crew, I really meant that I reported to the SOTEX representative (bird dog) on the seismic crew. I was the Junior Bird Dog.

I was told by the Senior Bird Dog to take a half day off and find living accommodations, which I did. It was a nice furnished house. The only thing I had to buy was a trash can. The objective of the seis crew was to run a few lines over a salt dome named Damon Mound. I expected to see a mound, but it looked quite flat to me. We (family) were happy for two rainy weeks. Then the Seis Crew bogged down, and the crew was moved to another town many miles away! We acquired a trailer and a trailer hitch to carry our stuff. I think we moved about thirty times in the following three years, but not with the same crew. We were moved from one crew to another. All this moving was caused by our style of using geophysics. We didn't do large surveys. When the Exploration people came up with a prospect, we shot a line or two over it and then moved on.

I know this sounds bad, but it was great training. A geophysicist had a three-year tour. A geologist got two years. The Party Chief ran the crew and mapped the data. The Senior Bird Dog made a map of the same data. The Junior Bird Dog usually mapped a shallow horizon. This training was supervised by a Senior Geophysicist in Houston. That person was Chuck Edwards, who was destined to become the Chief Geophysicist of the Chevron Corporation, reporting to a member of the Board of Directors. Sadly, Chuck died on December 30, a couple of days before the new decade. He was 95. His death has brought back memories of my first three years with SOTEX, as well as my next thirty-six years with Chevron. When Chuck retired, I assumed his role and retired in 1995. Chuck was a good supervisor and a great friend. □

# A Live Webinar

Sponsored Jointly by the SEG and GSH

SOCIETY OF EXPLORATION GEOPHYSICISTS

## PRACTICAL SEISMIC PETROPHYSICS: THE EFFECTIVE USE OF LOG DATA FOR SEISMIC ANALYSIS

**Four Half-days (9 AM - 1 PM Houston Time) March 23-26, 2021**

*Includes a 2-3 hour primer on sonic and density logs presented by* ***Matthew Blyth****, Schlumberger Well Construction.*

*Presented by*

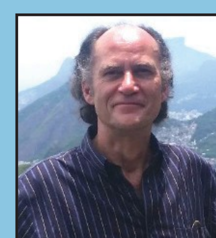
*Tad Smith, PhD, Geology*

This class will focus on the important role of "seismic petrophysics" in the quest to extract additional information from subtle seismic responses. Some of the topics covered will include important background information, relevant aspects of petrophysical interpretation, various aspects of log editing, and the basics of elasticity and rock physics. We will spend considerable time discussing some common pitfalls associated with the "workhorses" of rock physics, including invasion corrections, problems associated with shear velocity estimation, and some of the challenges and pitfalls associated with Gassmann fluid substitution. It is important to recognize that log data should not simply be recomputed to fit prior expectations as defined by a rock physics model. Instead, rock physics models should be used as templates, which allow the interpreter to better understand the underlying physics of observed log responses and how they are governed by local petrophysical properties. Case studies and hands-on exercises will be used to reinforce critical concepts.

This **16 hour course** can be taken in the comfort of **your office** or even **your own home**. It works on **PC's, iPads, iPhones**, or even two tin cans with a taut string (not recommended). **No travel costs**.
**The Course Fee: $390!** With major discounts for Groups and Students. 1.6 CEU's are awarded.
All Sessions are recorded for future viewing if you miss a session

**Visit gshtx.org, Events Tab to register and see expanded Course and Presenter Information**

# A Live Webinar!



## Velocities, Imaging, and Waveform Inversion

***The Evolution of Characterising the Earth's Subsurface***

**Featuring Dr. Ian F. Jones - ION Geophysical**

**April 12 - 15, 2021 9:00 am – 1:00 pm Houston Time**

The course is designed for practising geoscientists and geoscience students who desire a better understanding of the principles and limitations of both current and emerging technologies involved in subsurface parameter estimation and imaging. The material is designed to help readers better understand how contemporary velocity estimation methods work, and what approximations are involved in obtaining computationally tractable solutions. The evolution of the industry's approaches to building earth models with ray tomography and full waveform inversion is covered, as are some of the emerging possibilities for replacing imaging techniques with direct subsurface parameter inversion methods. The approach will be mostly non-mathematical, concentrating on an intuitive understanding of the principles, demonstrating them via case histories.

This **16 hour course** can be taken in the comfort of **your office** or even **your own home**. It works on **PC's, iPads, iPhones**, or even two tin cans with a taut string (not recommended). **No travel costs**.
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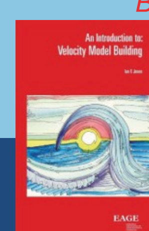
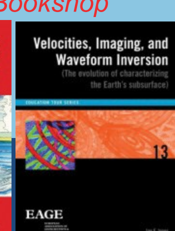



**Register now at: gshtx.org and seg.org**

All sessions are recorded and available on-demand to attendees.

# GSH Technical Events

## Rock Physics SIG
*New Inversion-based Rock Physics Method for Calibration of Seismic Inversion Products with Well Logs*
**Valeriia Sobolevskaia, Pursuing a doctorate in Geophysics at Rice University**
Abstract and Bio
Online presentation - March 3, 2021 - 12:00pm-1:00pm CST

Register

## Unconventionals SIG
*Setting New Standards for High Density Seismic Acquisition in the Permian- We Asked, Listened and Solved...*
**Anastasia Poole, Vasudhaven (Sudha) Sudhakar, WesternGeco**
Abstract and Bio
Online presentation - March 4, 2021 - 12:00pm-1:00pm CST

Register

## UH 27th Annual Milton B. Dobrin Lecture:
*Spanning Hydrocarbons to Humanitarianism: Where is Geophysics Going?*
**Maurice Nessim - President of the Society of Exploration Geophysicists**
**Paul Bauman - first SEG Humanitarian Award Winner**
**Andy Sabin - Board of Directors of the Geothermal Resources Council**
Abstract and Bio
Online presentation - March 8, 2021 - 5:00pm-8:30pm CST

Register

## Data Processing & Acquisition SIG
*Time-Lapse FWI Studies for 4D Seismic Data*
**Weizhong Wang, GeoTomo**
Abstract and Bio
Online presentation - March 9, 2021 - 5:00pm-6:00pm CST

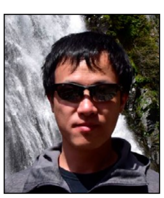
Register

## Technical Lunch
*Full Bandwidth FWI*
**Tatiana Kalinicheva, Fullwave at Imperial College London**
Abstract and Bio
Online presentation - March 9, 2021 - 11:00am-12:00pm CST

Register

## Data Science and Machine Learning SIG
*Opportunities and Challenges of Deep Learning in E&P: A Sneak Peek on a Couple Applications*
**Pandu Devarakota, Shell Global Solutions**
Abstract and Bio
Online presentation - March 10, 2021 - 11:00am-12:00pm CST

Register



## Potential Fields
*Gravity Constraints on the Tectonic Evolution of the Sea of Okhotsk, Northwestern Pacific Ocean*
**Lei Sun, University of Houston**
Abstract and Bio
Online presentation - March 18, 2021 - 4:00pm-5:00pm CST

Register

## NextGen: Under a Different Rock
*Under a Different Rock Series: Geophysical Applications in Mineral Resources*
**Dr. Mel Best**
Abstract and Bio
Online presentation - March 24, 2021 - 6:00pm-7:00pm CST

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## April 27th-28th 2021

JOIN US FOR AN EXCITING AND INTERACTIVE SYMPOSIUM ON HOW DATA SCIENCE WILL HELP DRIVE THE FUTURE OF GEOPHYSICS.

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WWW.GSHTX.ORG/SYMPOSIUM2021

GEOPHYSICAL SOCIETY HOUSTON

SEG

# Importance of Monitoring Seismicity Induced by $CO_2$ Sequestration at Illinois Basin – Decatur Project

*Frantisek Stanek*, Seismik s.r.o./Colorado School of Mines; Sherilyn Williams-Stroud, and Bauer, Robert, Illinois State Geological Survey (ISGS); and Leo Eisner, Seismik s.r.o.*

## Summary

Processing of combined microseismic data from two independent sparse seismic monitoring networks deployed at the (near-)surface around the Illinois Basin – Decatur Project (IBDP) injection site was done to characterize the detected seismicity by locations and inverted source mechanisms. By employing waveform similarity analyses, consistent processing was achieved for similar events, making it possible to distinguish between different clusters of events. The seismicity response was observed to vary with injection location. Different clusters and trends of locations in space and time support an interpretation of activated (mostly previously unknown) faults. Magnitudes of the observed seismic events range from -2.1 to 1.2, no felt event was recorded. Source mechanisms of the stronger events inverted from body-wave arrival amplitudes show that the activated faults are dominated by strike-slip and oblique-slip type of failure. Identified faults are interpretable in the recently reprocessed 3D reflection seismic data volume, which helped to confirm the existence of faulting in some of the locations where microseismicity was detected. This study shows that continuous microseismic monitoring, and updated processing of 3D seismic volume with a special focus on areas where microseismicity is observed helps to better understand the response of the reservoir to $CO_2$ injection.

## Introduction

Injection-induced seismicity is one of the major concerns for most of the operators involved in underground injections such as a stimulation of hydrocarbon bearing reservoirs, creating fluid paths through the rock for geothermal projects, or storage for wastewater, carbon dioxide ($CO_2$) or natural gas. There are several cases with reported felt, sometimes even damaging, seismicity, for example, wastewater injections in Oklahoma (Barbour et al., 2017; Schoenball and Ellsworth, 2017), geothermal operations in Pohang (Kim et al., 2018) or Basel (Deichmann and Giardini, 2009), or hydraulic fracturing operations in Canada (van der Baan and Calixto, 2017) or UK (Clarke et al., 2014). However, $CO_2$ sequestrations are not connected with any reported felt seismicity (Rinaldi et al., 2014), while potential of induced seismicity is considered one of critically limiting factors (together with a leakage potential) for operations on a scale needed to change the global climate.

The raised awareness of a potential risk increased a demand for understanding of an actual reservoir response to injection, and for evaluating the hazard and effective control of induced seismicity (for example the Traffic Light System, Haring et al., 2008). The most important seems to be the knowledge of existence of pre-existing faults that may be present in the reservoir and can potentially be reactivated from the increased pressure. Unfortunately, sometimes even from high-quality 3D reflection seismic data it is difficult to map all the faults, especially strike-slip faults. Therefore, a passive seismic monitoring of microseismic activity before, during and after an injection is crucial for mapping faults susceptible to slip. Source mechanisms of induced micro-earthquakes provide information about size and orientation of faults and the stress field responsible for the slip.

## Project Description

Illinois Basin – Decatur Project (IBDP) funded by U.S. Department of Energy is led by the Illinois State Geological Survey (ISGS). $CO_2$ is being injected into a few hundred meters thick sandstone reservoir at a depth around 2 km. There are two injection wells, CCS1 and CCS2 *(Figure 1)*. Into the well CCS1 were injected 1.1 million tons of $CO_2$ from November 2011 to November 2014. Injection into the second well, CCS2, started in 2017 with the planned target volume for both wells of 5 million tons

*Technical Article continued on page 11.*

Technical Article continued from page 10.

in 5 years. However, the current average injection rate is about 570,000 tons per year.

The Illinois Basin covers most of the Illinois and partly also the states of Indiana and Kentucky. At maximum the basin is 380 km wide and 650 km long and intersects a part of the well-known New Madrid Fault Zone in the southern end of the basin where the geological complexity coincides spatially with relatively high natural earthquake activity. The area of central Illinois where the CCS project takes place is, in comparison, seismically very calm with minimum earthquakes. A possible explanation for this observation could be that the structure of central part of the basin is less complex than the southern part with the New Madrid Fault Zone where the faults are big and easy to identify in reflection seismic data.

The target formation, the Mt. Simon Sandstone, is described in detail from core analyses, well logs and using 2D regional reflection seismic data and repeated 3D reflection seismic surveys (Freiburg et al., 2014). *Figure 1* shows reflection seismic acquisition survey configuration. The 3D seismic data were used for planning drilling and characterization of the $CO_2$ plume area and a second acquisition after injection into the CCS1 well ceased made possible 4D, time-lapse, monitoring. In the vicinity of the IBDP injection wells, the reservoir thickness is almost 800 m and different lithostratigraphy for Lower, Middle and Upper zones (Freiburg et al., 2014). The Lower section of Mt. Simon

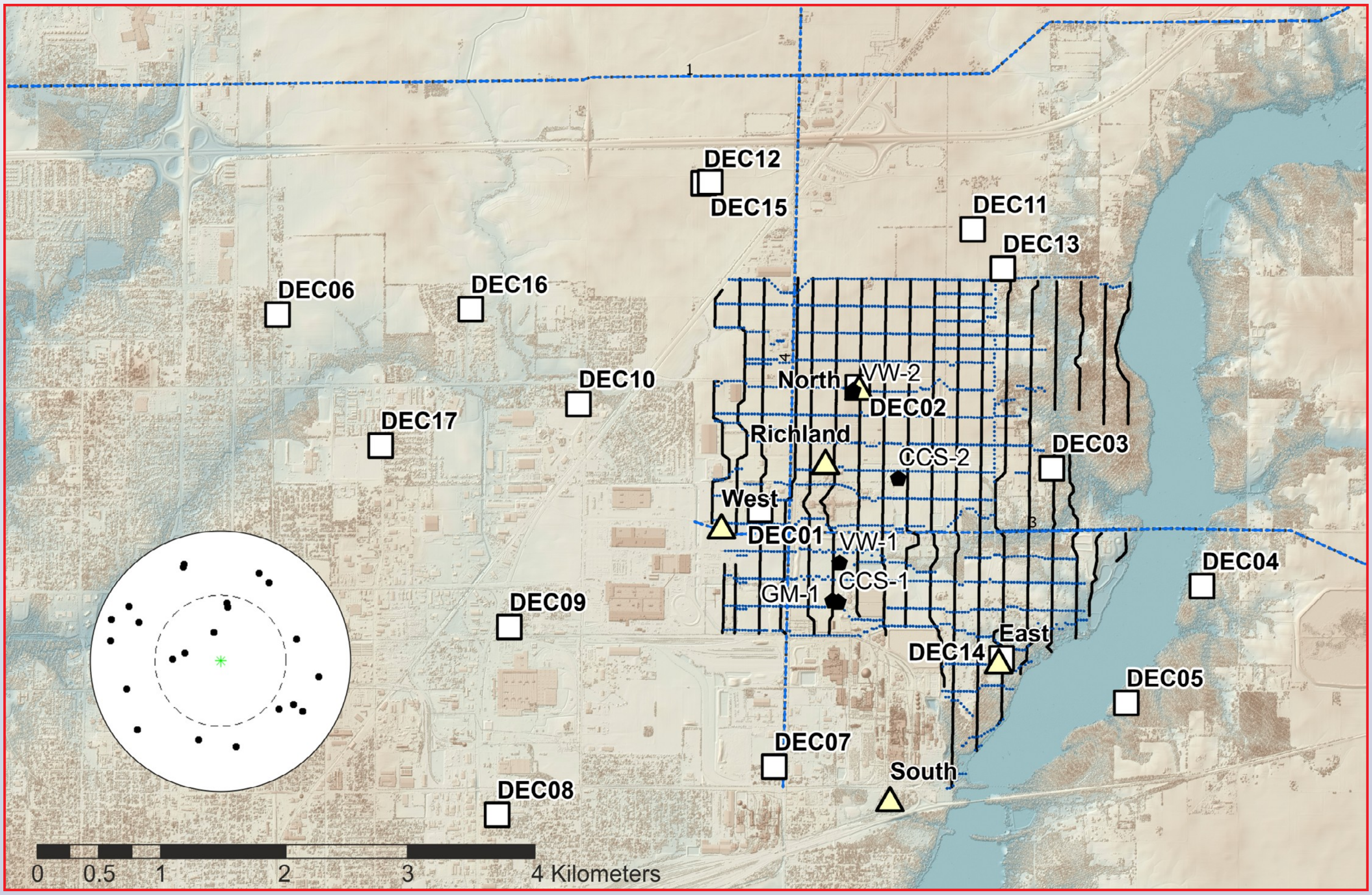


*Figure 1: Map of the active and passive seismic acquisition configurations for the IBDP. The grid of blue and black lines (~ 10 km$^2$) 3D seismic footprint. The long blue lines show the traces of 3 of the 4 2D seismic lines, the white squares and yellow triangles are USGS and ISGS seismometers, respectively. The two injection wells, CCS1 and CCS2 and monitoring wells are indicated by the black symbols. The circle on the left shows positions of surface stations on a unit focal sphere around the hypocenter below the center of array at the average depth of observed seismicity.*

Technical Article continued on page 12.

Technical Article continued from page 11.

Sandstone was selected as the best for the $CO_2$ injection due to porosity (~22%) and permeability (as high as 1000 mD). The overlying Eau Claire shale works as a sealing layer for potential upward migration of fluids. The basement rock, separated in most areas from the Mt. Simon by the informally named Argenta formation composed of argillaceous siliciclastics, consists of crystalline igneous rocks.

The stress field measurements in the central part of Illinois Basin (Bauer, 2019) indicate the orientation of horizontal maximum stress axis in NE direction.

## Passive Seismic Monitoring Arrays

This study discusses one of the best monitoring sites in the world for large scale $CO_2$ injection. There is a continuous monitoring system using both borehole and (near-) surface monitoring arrays installed to get information about seismic velocities and record wavefield created by microseismicity. In the CCS1 well are two 4C geophones approximately at the depth of injection (Bauer et al., 2019). The adjacent GM1 well hosts 31 3C geophone array, placed in shallower depth above the injection point, installed for repeat VSP acquisition, but also used for microseismic monitoring. There were also five 3C geophones temporarily installed in the verification well (VW2). Data from sonic logs acquired in the wells VW1 and CCS1 were also used for building velocity model needed to process passive seismic data.

The (near-) surface array consists of 17 stations (with names DEC) deployed by the USGS approximately 18 months after the start of injection (Kaven et al., 2015), and 5 stations (named East, West, South, North, Richland) run by the ISGS. In total, 22 stations within 5 km from injection wells form surface monitoring network *(Figure 1)*. Such configuration provides receiver focal coverage of the area *(circle on the left in Figure 1)* ideal for accurate determination of source mechanisms for local seismic events.

## Observed Microseismicity

The observed microseismicity provides great insight into the reservoir response to injection. The multiple monitoring arrays and continuous measurements made it possible to follow spatial-temporal changes in seismicity.

Monitoring using borehole arrays started approximately 18 months before the first CCS1 injection in order to understand background (micro-)seismicity in the vicinity of IBDP injection site (Smith and Jaques, 2016). In the pre-injection period, there were mostly detected signals related to drilling operations, events from distant mine/quarry, several distant earthquakes (reported also by USGS) and only 8 local microseismic events indicating low natural background seismicity. Carbon dioxide injection into the CCS1 well, starting in November 2011, and the seismicity started to appear one month later. There were a few events in the first 2 months and then an increase of than 500 events in February 2012. None of the following months showed a higher count, with subsequent seismic activity mostly ranging from 50-200 events per month. Only in 4 other months the rate was higher than 200 events/month *(see histogram in Figure 2)*. The injection into CCS1 well ceased at the end of November 2014. These events form several spatial clusters elongated either close to the direction of observed maximum horizontal stress in the region (68°) or in EW direction *(Figure 2)*. Seismic activity decreased to less than 20 events per month over a period of about 6 months after the end of CCS1 injection.

In April 2017, the injection into the CCS2 well started but the number of induced microseismic events has not significantly increased in comparison to the event rates during the non-injection period. This is interpreted to be due to shallower injection interval depth than in the case of CCS1 well, despite the CCS2 injection rate being approximately 1.7 times higher.

The total number of detected and located events by downhole arrays through November 2019 is 5,501, with 96% of the total recorded before the start of CCS2 injection.

In 2015, USGS (Kaven et al., 2015) published locations and a few main types of source mechanisms for 150 events detected by USGS surface stations in the period from July 2013 to February 2015. The lower number of events, and the higher minimum magnitude (-1.3) than for the events detected by

Technical Article continued on page 13.

Technical Article continued from page 12.

borehole array is understandable because the sensitivity of the surface array is lower mainly due to greater distance from the source area. On the other hand, the advantage of surface array is that it provides much better focal sphere coverage and so better conditions for stable source mechanism inversion.

A more detailed processing and results for a subset of events detected by surface array is presented here. Selection of 50 events was based on signal-to-noise ratio. The magnitudes of selected events range from -1.0 to 0.9. In comparison to results of Kaven et al. (2015), we have used data not only from all available USGS stations but also from the 5 ISGS seismometers installed at the site.

The initial focus was on finding events with similar waveforms and consistent picking of P- and S-wave arrivals *(see example in Figure 3)*. The goal was to reduce uncertainty of picked arrival times, decrease uncertainty of location and get events with similar differences between P- and S- wave arrival times observed on each station located close to each other, i.e. reduce scatter of locations. However, sometimes even very similar events are not located as close to each other as may be expected because of different numbers of available picks (stations with good signal). For some events the missing or noisy data from one or more stations makes the location different. The higher location instability may be observed especially when a different number of picks combines with an uncertain velocity model. Two

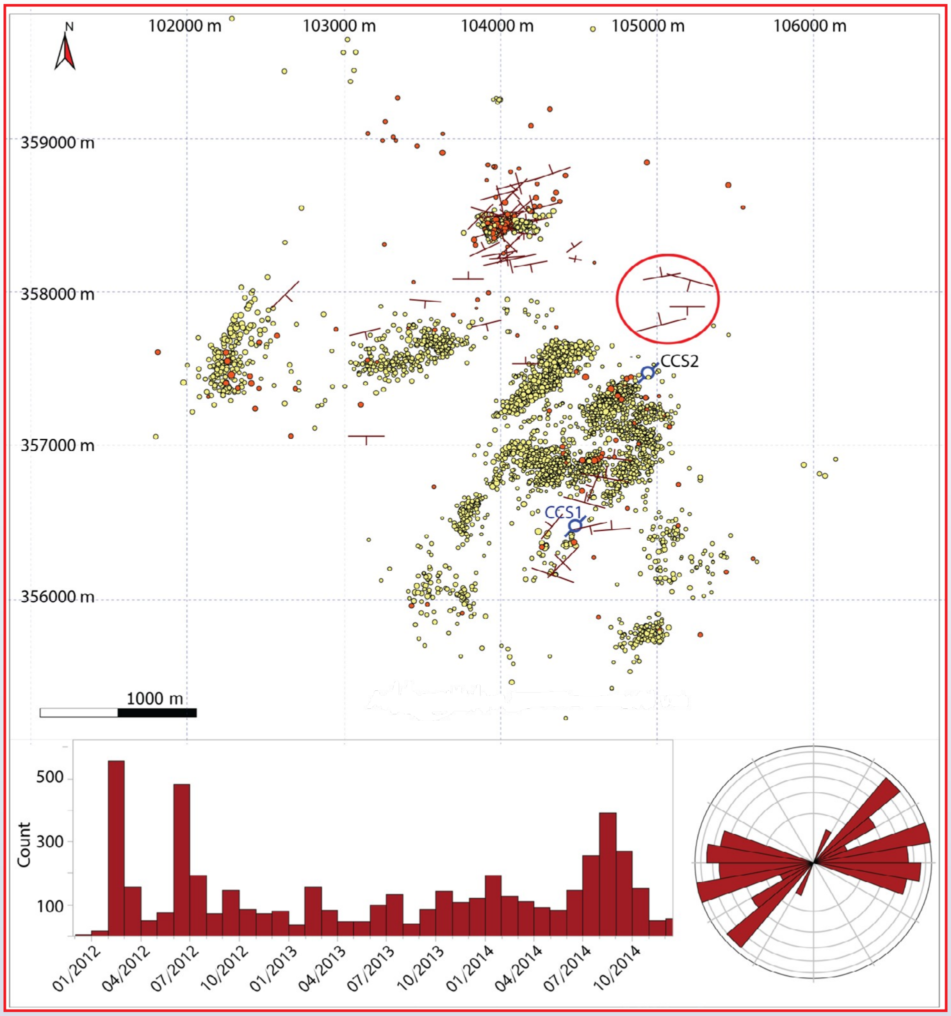


*Figure 2: Map of induced seismicity during injection in the CCS1 well. Yellow dots are epicenter locations of downhole sensor detected events; orange dots are epicenters of USGS seismometer catalog detected by the local GS-DEC network. The strike-dip symbols are centered on the epicenters of the events located using the USGS seismometers and the 5 ISGS stations on the surface at the IBDP site, without using additional constraints from downhole data. The rose diagram shows the (bidirectional) strike azimuth of the source mechanism failure planes. The histogram shows the frequency of events per month for the entire injection period of CCS1. The four strike-dip symbols in the red circle are centered on event locations that have high location uncertainty. See text for explanation.*

major groups of similar events were identified, consisting of 41 (80%) of the re-processed events. Some of the events that were located using only the surface seismometers are outside of the spatial clusters. These events have unique waveforms, different from the events located in the clusters, therefore their location uncertainty may be higher due to higher picking and velocity model uncertainties.

Similarity of waveforms does mean that the events have also similar source mechanism. A grid search was employed to find a

Technical Article continued on page 14.

*Technical Article continued from page 13.*

pure shear source mechanism described by strike, dip and rake angles and seismic moment that fit the best observed body wave arrival amplitudes (e.g., Stanek et al., 2014). Data from all available stations was used but in cases with some stations missing, or arrival time could not be picked with a high level of certainty, those stations were not used for the inversion. Similarly, as for locations, differences in data availability cause differences in the resulting source mechanisms even for highly similar events, especially when it is combined with uncertainties of location and modelling of wave propagation through the given velocity model. The event epicenters determined from the surface stations only are centered on the dip symbols on the map in *Figure 2*. Failure plane orientations are dominated by strike-slip, with a range of azimuths similar to the elongation trends of the microseismicity clusters. The failure plane orientations not always but usually correspond to the orientation trends of the microseismicity clusters.

In both, location and source mechanism inversion, we found the addition of the data recorded by the ISGS stations to be important. The stations are deployed close to the center of the array where most of the seismic activity takes place and an uncertainty of results decreases when data of ISGS stations can be used together with data from USGS stations.

## Importance of Using Passive Seismic Data

Small events are observed in clusters located slightly above or below the bottom of the target reservoir. Fluid propagation into the basement could have occurred through high permeability pathways such as fracture corridors, which could lead to re-activation of faults in the

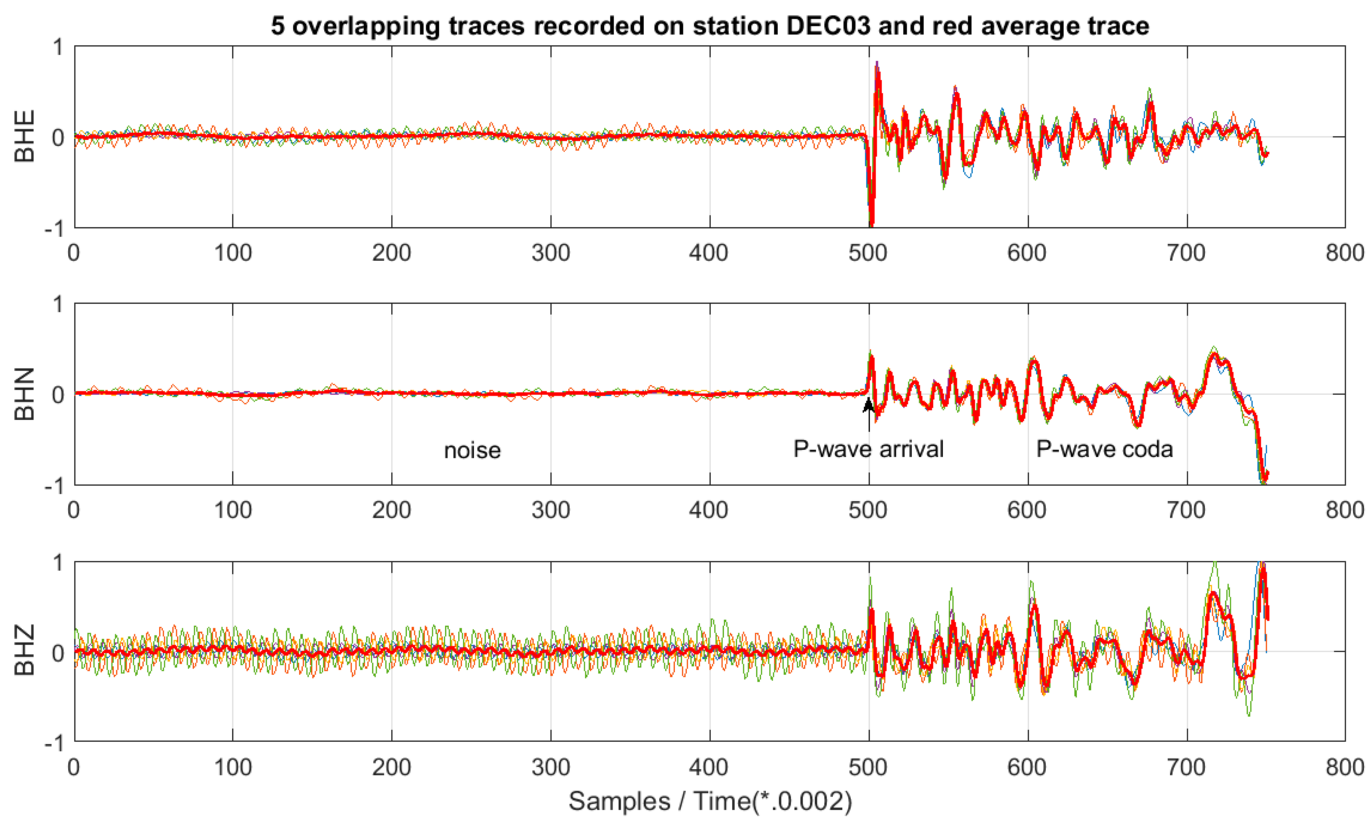


*Figure 3: Example of waveform similarity. Here are shown overlapped normalized waveforms of 5 events recorded by station DEC03. The waveforms of East (top panel), North (middle panel) and Vertical (bottom panel) components are aligned on the P-pick (sample 500). The red line represents average waveform of the shown waveforms.*

*Technical Article continued on page 15.*

*Technical Article continued from page 14.*

basement rock. The geology and structure of the reservoir and basement rocks of at the IBDP site appears to respond with relatively small magnitude induced seismicity when compared to wastewater injection in Oklahoma, for instance, although the reasons for this are still not clear. The small offset faults in the subsurface at the IBDP site are difficult to identify in active seismic imaging and suggest that the surface area of existing faults is also relatively small. This study shows that combination of active and passive seismic helps to better understand the response of the reservoir to injection, in this case $CO_2$ injection. Knowledge of faults that might be potentially a source of felt seismicity is critical for project success and should be included in the site assessment (William-Stroud et al., 2020). The microseismicity is an extremely useful type of data for revealing the hidden faults, but it is generally not available until after the start of the injection operations. Consequently, it is even more critical to include high-quality reflection seismic data acquisition and processing and as part of a $CO_2$ injection project. Ideally, real-time analyses of passive seismic data for this type of monitoring may play a key role in a real-time decision making and mitigating induced seismicity hazard. Good reservoir models can be improved over time with incorporation of new data to allow more accurate hazard evaluation and successful fulfilling goals of projects.

## Acknowledgments

This project is funded by the U.S. Department of Energy through the National Energy Technology Laboratory (NETL), under agreement DE-FC26-05NT42588. The authors would like to thank the USGS for providing their event catalog and useful discussions concerning the data, and to thank Sterling Seismic Services for informative discussions on their seismic reprocessing results, and Petroleum Experts for their donation of MOVE software and Schlumberger for their donation of Petrel software, which were used to model and analyze data for this project. □

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Permalink: https://doi.org/10.1190/segam2020-3427548.1

# GSH Movie Time

## Now Showing

## The Total Seismic Environment*

### Lecture by John Wardel – 1982

This movie is a continuation of the "Introduction to the Seismic Reflection Method of Prospecting" presented in the September 2020 issue of the GSH journal.

In the previous lecture we looked at how seismic energy travels through the earth, different kinds of wave motion and how seismic energy is reflected from interfaces between different rocks. We also looked at the basic elements of the system used to record these reflections and how reflections are displayed to give a picture of the rocks' structures in the earth.

In this lecture we look at different kinds of reflections and events that occur, and how these appear on the recorded seismic traces. The events analyzed include: Primary reflections, Multiple Reflections, Reverberations and Ghosts.

* GSI vintage videos courtesy of Schlumberger – WesternGeco

# Tutorial Nuggets
*By Mike Graul*

## The Guru Delves Deep into Bayes' Theorem

Guru works up sweat digging into Bayes

**[A Note from the GSH Editorial Board**. The ever-enigmatic Guru left another bewildered group of readers (3) pondering his reference to "**DMP**" and its loose connection to a blatant **piece of fiction** called the "**Tommie Rape disease**". This was revealed after a rather curt and threatening letter was received from **Tommie's snarling lawyers**. Our deepest apologies to Tommie for the unwarranted attack by the Guru.

The actual initials by which **dermothermalplastosis** is known to medical professionals is **DTP**. Correction to this effect are made in the restatement of the **March Puzzle**, below.**]**

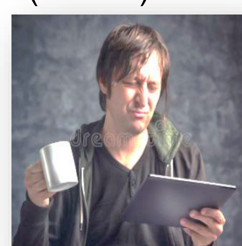
**Solution to Puzzle for March 2021**. While we're on **Bayes**, let's try this one. (One day, in the unlikely occurrence of a pandemic, you may wish to consider problems of this type.)

Suppose a screening test for Dermothermalplastosis (~~**DMP** or the **Tommie Rape disease**~~) **DTP** has a **false positive rate = 1% (or 99% true positive rate)** and a **false negative rate = 1% (or 99% true negative rate).** Further, the rate of the disease in the **U.S. population = 0.002 (if the population of the U.S. is ball-parked as 330,000,000, this would mean about 660,000 actual cases walk among us).** Most of the diseased are **highly contagious**, especially in the ugly **fulminating** and **flaking** stage. The only known method for full suppression of these ghastly symptoms is to keep the **DTP** patient at a sustained temperature < 60°F (not fun).

Dr Condenado

"Haynie, your DTP test came back positive. You will have to quarantine yourself in the Cold Room until further notice."

- Dr Candenado to Haynie on a Doom Zoom Appointment



Hapless Haynie

Is Haynie's life pretty much over as he once knew it?. Does the fact that the test is **99% correct** mean there is no statistical wiggle room for Haynie hope for a reprieve? Not necessarily. What often gets overlooked or misunderstood when non-statisticians are assessing the likelihood (probability) that they have the disease when testing positive are the following: First, consider from what **population** were you and the other testees drawn? Let's assume it was from a large sampling of the 50,000 employees of your company throughout the US. This is a **random sampling** as opposed to sampling of people known to **have DTP** (for the 99 % true positive test) or a group of folks **not diseased** (for the 99% true negative test).

**S**econdly, what is the probability of testing positive in a random sampling? This requires a rate (probability) of actually having DTP which we show above to be **P(H) = .002 = 0.2%.** Now we're ready to help poor Haynie.

*Tutorial Nuggets continued on page 18.*

*Tutorial Nuggets continued from page 17.*

Let's rewrite **Rev. Tom's theorem** in terms related to these tests and critical questions.

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \Rightarrow \quad P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

Events: A ⇒ H = Has disease. This is the **H**ypothesis
B ⇒ D = Test + = All possible ways of Testing +

**S**o, we are testing and evaluating the hypothesis the probability Haynie really **has DTP** given the positive test results, P(H|D). The P(H) is the rate of real DTP in the USA (.002). The P(D = Test+), but we must consider both the P(false positive as well as the false negative test, along with the over all P(H).

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

P(H) = .002
P(D = T+) = P(D|H) + P(D | NotH)
= (.99)(.002) + (.01)(.998)

$$P(H|D) = \frac{(.99)(.002)}{(.99).002)+(.01).998)} \approx 0.166 = 16.6\%$$

**T**his is not a criticism of the test protocol – it is no doubt a fine test with the quoted **P(D+|H) = .99**, but this is not the **relevant statistic** for guys like **Haynie** who appreciates the **"sensitivity"** (as the medical community refers to it), but really wants to know the probability that **he has DTP after testing positive**. He should still quarantine, but his chances of having **DTP** has been reduced significantly when all data is used.

**T**his same concept is what fakes people out in trying to fathom why the guest should switch her choice in the case stated. See if you can set up the Bayes Theorem to show why switching doubles your probability of winning the **Rolls Royce Phantom.**

**W**e'll consider one additional application in the of Bayes in checking on mandatory drug testing now in widespread corporate use. Baseball statistics have long been a hallowed hobby of the American Game of Baseball (applicable to Football, Basketball, and Pub Dart throwing as well as well).

*Tutorial Nuggets continued on page 19.*

# Tutorial Nuggets

*Tutorial Nuggets continued from page 18.*

**S**teroid use facilitates the **580-foot HR**, the **80 yard-in-the-air TD**, the **20th 3-pointer from half-court** in the NBA single **game record book**, and the **GSH King's Pub & Grill** Thursday Night Double-In–Double-Out-301-Game All-Time Record of **87 straight wins** by "The Executives". (The dart board and back wall needed replacement nine times during their fabulous run). **The Guru,** widely suspected of blatant steroid abuse, flexes for his adoring public, at the right. He denies all allegations of steroid use or abuse or misuse, and is a staunch advocate of **outlawing drug testing** of all kinds

**Guru? Capable of Damn-Near Anything**

**D**espite the **Guru's objections**, most ball clubs, mandated to do so by the **NFL, MLB, NBA, and NDA**, are requiring **Steroid Testing** of all roster athletes. Let's look at the sad case of **Bobby Pure, RF, Houston Astros**, **2016- 2020,** forced to retired at **age 28** after **testing positive** for steroid abuse (and having a 5-year batting average of **.437).**

**G**iven that Bobby tests **positive,** what is the probability that he really is using steroids? Since the test is rated accurate 95 percent of the time, i.e., **P(D=T+ | H) = .95**, the naïve answer would be that Probability of Booby being guilty is **95 percent**. But a **Bayesian** knows that such a conclusion cannot be drawn from the test alone. We would need to know some additional facts not included in this evidence. In this case, you need to know how many baseball players use steroids to begin with — that would be what a Bayesian would call the prior probability.

**Jack of all Trades**

**F**or that information, we turn to the **Houston Texan's beloved Jack Easterby,** Pastor, part-time President, Player Disciplinarian, and Statistical Cognoscente for the **Houston Astros.** He informs the *GSH Journal* that some **5 percent** of **MLB players use steroids** (and Jack knows who they are and where they live). Now we can produce a Statistical Summary and determine the probability that Bobby has really been (gasp) using steroids.

**P(D=T+ | H) = .95 True Positive ……….P(D = T+ | NotH) = .05 False Positive**
**P(D = T- | NotH) = .95 True Negative ……P(D = T- | H) .05 False Negative**
**P(H) = 0.05 Use of steroids by MLB players**
**Determine P(H | D) the probability that Bobby is really using Steroids**

Be sure to find (elsewhere in this Journal) and read about the GSH-SEG New Model of learning by Webinar launching March 1, 2021 with the Presentation of Machine Learning & Artificial Intelligence Learn at Your Pace – On your Schedule
**Register Today and Take a full 4 months to absorb this Hot Topic**

For questions or sponsorship opportunities, please contact:
Scott Sutherland, Scott.Sutherland@CGG.com 346-366-0288


# GSH Legacy

The GSH has been honored in the past to have received substantial support from members who have designated such at their passing. We are now beginning an official GSH Charitable Bequest Program and we would like to invite you to participate. This GSH program can help provide financial stability for the GSH, allow for long term planning of the society and allow you to honor your years in the geophysical profession. You will be recognized for your participation in this program on a Legacy of Geophysics page on the GSH website unless you choose to remain anonymous.

There are a variety of ways to participate. Some are listed below. There may be tax advantages to you in some situations, but you will need to consult your personal tax advisor for that determination as GSH cannot provide tax advice. Charitable bequests that are undesignated will be used for the general operating expenses of the GSH. Bequests may be designated for specific programs such as Scholarships, the Geoscience Center, Outreach, or others.

Some of the options for participation are:

----Gifts can be made by beneficiary, partial beneficiary, or contingent beneficiary designation in a retirement account, a certificate of deposit, a bank or brokerage account, or a life insurance policy.

----Gifts can be made through wills or trusts. You can designate a specific dollar amount, a particular asset, or a percentage of your estate.

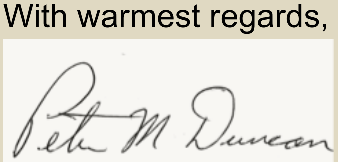
----Gifts can be made through your IRA if you are over the age of 70 ½, and your gift can count toward your Required Minimum Distribution and be excluded from your gross income.

----Gifts can be made with stock or in cash.

If this program is of interest to you, your attorney or financial advisor can provide more information and the appropriate forms. If you would like to know more about how such a bequest could benefit the GSH please contact the office at 281-741-1624 or by email: karen@gshtx.org. We would like you to let us know if you have made such a bequest so that you may be properly recognized by the society.

I hope many of you will see a gift of this nature as a meaningful way to celebrate what geophysics and the local community have meant to you. Please consider a lasting gift to the GSH.

With warmest regards,

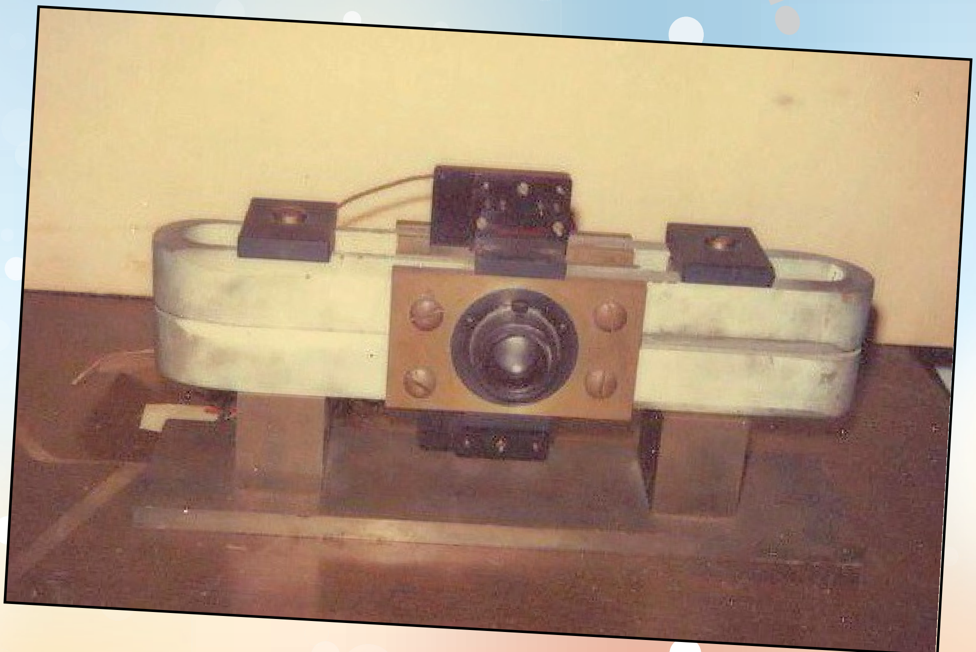


GSH President 2020-2021

## Mystery Item

*This is a geophysical item...*

*Do you know what it is?*



*This month's answer on page 24.*

The Mystery Item
on page 22
is a
**Four-trace galvanometer from 1930. Donated by Sun Oil.**

## Corporate Members





## Item Of Interest

In 1735, Pierre Bouguer, while on an expedition to Peru, used the pendulum to indicate gravity anomalies and in 1740 made the first attempt to evaluate the density of the Earth. Gravity data is reduced to Bouguer maps, i.e., corrections for elevation above and below a given datum. □

The GSH – SEG Announce
A New Paradigm in Webinar Courses

# Learn Your Way – At Your Pace and Schedule

(Not Some Arbitrary Dates Set by The At My Convenience Committee)

Hot Topic Alert !

The Initial Offering of this Learning Model

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Part 1

March (1–31) | April (1–30) | May (1–31) | June (1–30)

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## Part 2 Neural Networks and Unsupervised Learning
## Part 3 Geophysical Applications with Codes and Demonstration

Parts 2 & 3

May (1–31) | June (1–30) | July (1–31) | August (1–31)

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# Geoscience Center

## *Beginnings of Bob Sheriff's Dictionary* By Les Denham

*1790 W. Sam Houston Pkwy. N. (Right on Shadow Wood)*

The bestselling book on geophysics is undoubtedly the Encyclopedic Dictionary of Exploration Geophysics compiled by the late Robert E. Sheriff, first published in 1973. Today, anyone attempting to write such a book would use a computer to save, organize, and format the document.

But in the 1960s, when Bob wrote the 30-page glossary which formed the basis of the dictionary, and even in the 1970s when the first edition was published, computers as we know them today did not exist. Certainly, computers did exist, but they were giant, expensive machines, reserved for special tasks which could not be done properly in any other way. The first personal computers usable for personal tasks such as writing a book did not appear until the middle to late 1970s.

So how did Bob keep track of his dictionary material? We have the answer to this question in the Houston Geoscience Center. Among the material donated to the Center by the Sheriff family is a two-drawer card file. Such files were common in offices and libraries fifty years ago.

Each of these drawers is crammed with cards (Figure 1), each card corresponding to an entry in the dictionary. Bob arranged them by subject matter (Figure 2): electromagnetics (EM), logging, temperature, computers, remote sensing, unclassified, etc., and alphabetically (as in the final dictionary).

On each card he pasted a clipping from his source material for a definition. The example shown in Figure 3 is an abstract of a paper published in Geophysics for February 1963.

When the dictionary was completed, the pages were typeset, and a galley proof printed (Figure 4). A true galley proof is printed from type set in galleys (the trays used for hand-set letterpress printing), intended for the author and editor to check the accuracy of the typesetting before the book is divided into pages, with the addition of page numbers and headings.

We can see from the galley proof that the book is not typeset in the traditional manner: it looks as if it was typed on a typewriter (all characters are the same font and size), and pasted onto pages, together with drafted figures. The figure number, however, is a different font and a different size.

Today, such a book could be completely typeset by the author, ready for the final printing. The author and editor still need to proof the book before it is published, but nothing need be printed on paper until the PDF file is finalized. We can admire the amount of work Bob Sheriff put into completing the first edition of this dictionary.

The library at the Houston Geoscience Center has copies of each edition of the original English dictionary, as well as copies of versions published in other languages, including Turkish, Spanish, and Mandarin. □

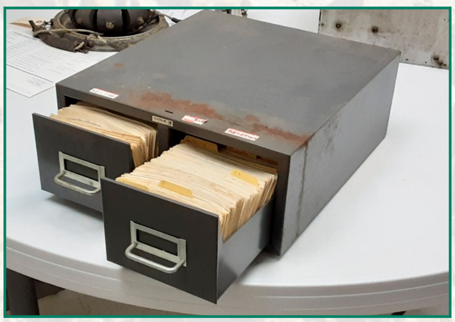

Figure 1: Full of Cards

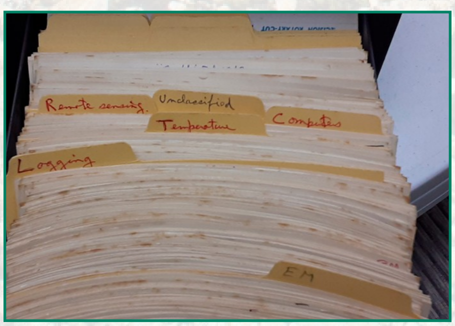


Figure 2: Arranged by Sugject

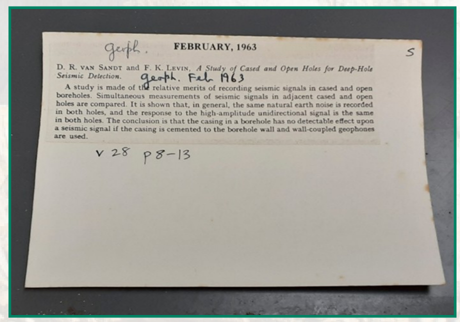


Figure 3: A Typical Card

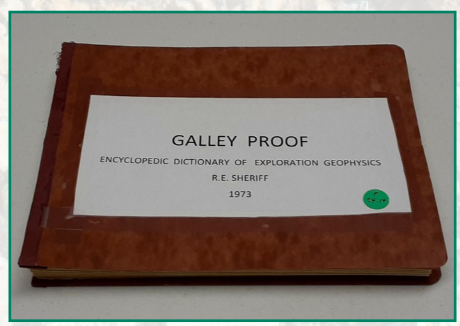


Figure 4: Gallery Proof

The Geoscience Center has been mostly closed due to the Covid-19 restrictions, but we are slowly opening again for a few people at a time. Usually there is someone there on Wednesday mornings from 9:00 until noon or by appointment and visitors are always welcome. Please contact me at: geogaf@hal-pc.org or by phone at: 281-370-3264 for more information.

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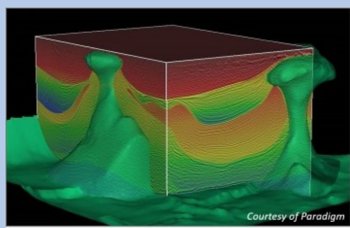


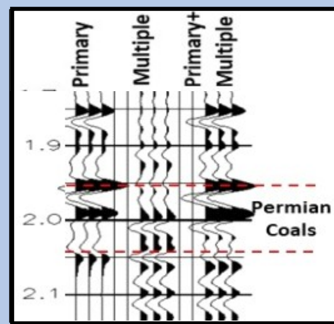


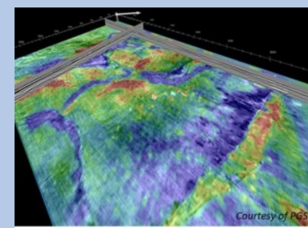


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|---|---|
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| – Beyond AVO to Quantitative Inversion Interpretation QII | Bill Goodway |
| – Affordable S-Wave Reflection Seismology | Bob Hardage |
| – Simplifying and Lowering the Cost of S-Wave Reflection Seismology | Bob Hardage |
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| – Geophysical Signal Processing 101 | Enders A. Robinson & Sven Treitel |
| – Seismic Amplitude 20/20: An Update and Forecast | Fred Hilterman & Mike Graul |
| – Extracting Geology from Seismic Data | Fred Schroeder |
| – Applied Azimuthal Anisotropy-Azimuthal 3D P-P Seismic: WHY Bother? | Dr. Heloise Lynn |
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# Doodlebugger Diary

## *A Doodlebugger's Experience with Doodlebugs*

*By Gene Sparkman*

*The Doodlebugger Diary recounts the experiences of geophysicists during their working lives. This month we have a guest article from a fellow doodlebugger whom many of you likely know given his extensive career in the industry.*

*Given the apparent interest in this topic, I will be following this segment up with a series on Doodlebugs. It should be enlightening if not entertaining.*

*If you have stories of your early career you would like to share, please send them my way. I will be happy to print them in this segment.*

I found Dan Plazak's contribution to the January edition of the GSH Journal Doodlebugger Diary entertaining. His description of "Pseudo-Geophysical Devices in Oil Exploration" reminded me of an experience from my ancient past which I would like to describe to you. After reading Dan's article I could not help but think that all of us old-timers deserve to be called "Doodlebuggers" because our work was considered "pseudo-geophysical", particularly by our engineering colleagues. Dan concluded his article by saying "Do not mourn the extinction of doodlebugs. They are still with us.", and with that as an introduction, here's my story:

In 1970 I was on the staff of El Paso Natural Gas where I heard a presentation made to the Chief Geophysicist on the application of electrical methods as a direct detection of hydrocarbons. The presenter described work that was ongoing with

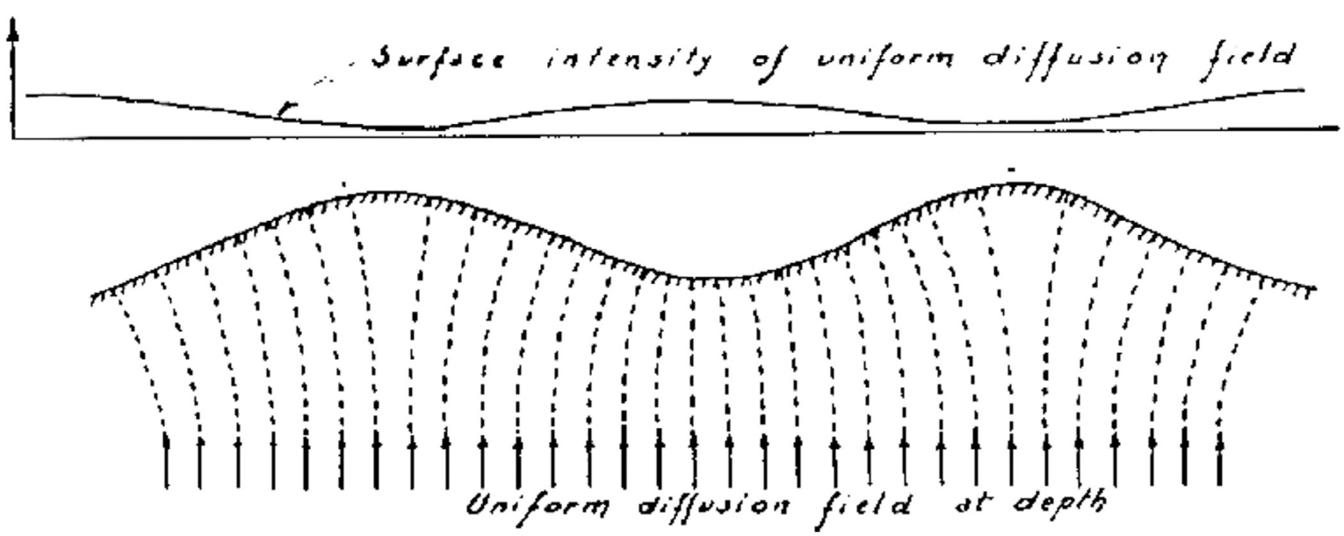


FIG. 1. Effect of topography on the observed intensity of a hydrocarbon diffusion field.

*Doodlebugger continued on page 31.*

*Doodlebugger continued from page 30.*

Dr. Sylvain Pirson, a professor at the University of Texas. Dr. Pirson was a renowned expert in well log interpretation and was a proponent of using self-potential (SP) measurements to identify the fuel cell effects from surface hydrocarbon seeps. Several of his articles from oil and gas periodicals were presented.

In 1979 I had another encounter with this same presenter. I was then Division Geophysicist in Tenneco's Oklahoma City Division. Tenneco was researching geochemical technologies for hydrocarbon detection. The geologic research group had us send a summer employee to the Texas Panhandle to collect cuttings from shot holes for geochemical analysis. The presenter had gotten the attention of the research group and they insisted that we try the technology.

We conducted a survey using this electrical surface measurement technique over a ranch in the Texas Panhandle where a drilling program was ongoing. The results were interpreted to correctly identify all existing wells whether productive or not. There was a well that we were in the process of drilling which the interpretation cleverly showed to be located at the edge of a positive anomaly. This created an uncertainty in the method as it did not clearly define the outcome of the well. After all, we know interpreters can slant results to fit preconceived notions. While it is common knowledge electrical methods have been used with positive results, this test did not convince us to proceed.

Interestingly, Dr. Pirson had previously published an article in Geophysics in 1946 titled Disturbing Factors in Geochemical Prospecting[1] where

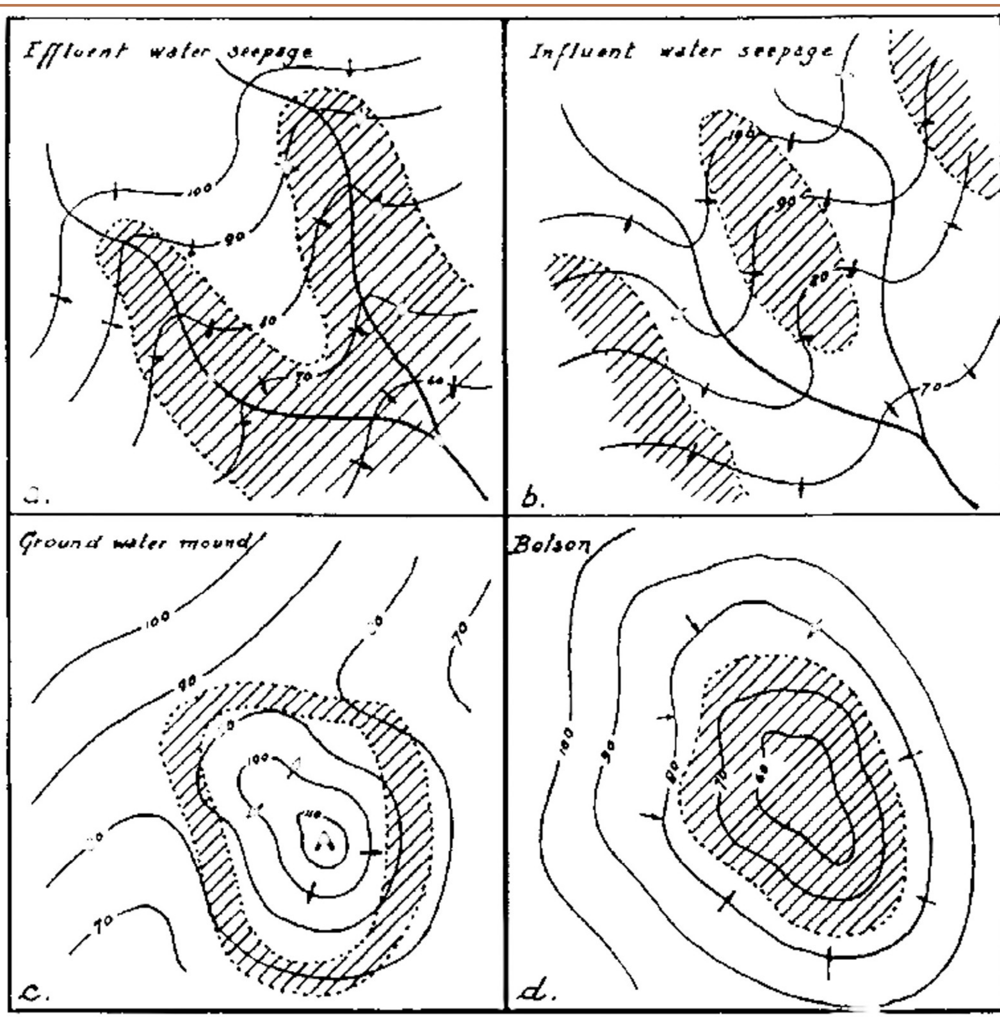


FIG. 2. Effect of water table movement on the observed intensity of a hydrocarbon diffusion field.

*Doodlebugger continued on page 32.*

*Doodlebugger continued from page 31.*

he describes an extensive attempt to identify geochemical measurements that could be used in oil and gas prospecting. He concluded that there were inconsistencies that preclude the reliable application of these technologies at the time. All of us field geophysicists can also point out numerous inconsistencies in the measurement tools, field techniques and interpretations that add to these uncertain results. Maybe this would also describe the results from our test. His abstract says:

> A review of the results of over 3,000 measurements of soil ethane emanation rate made over the past five years has revealed a number of conclusions which have an important bearing upon the validity of geochemical methods of prospecting for oil and gas fields. A number of factors have been found to be highly disturbing, namely: earth topography (Figure 1), ground water percolation and seepage (Figure 2), barometric pressure variations, etc. These effects result in fluctuations of the rate of escape of hydrocarbons accompanied by horizontal shifts of leakage which give rise to the creation of artificial leakage highs altogether meaningless from the point of view of oil and gas accumulation at depth. Certain qualitative rules of interpretation have been established which permit weeding out the meaningless anomalies provided sufficient information is at hand on the topography and water table movement.
>
> A further observation has been made indicating that the artificial anomalies are often of greater magnitude than the significant measurements. Hence the problems, so common in other geophysical methods, of making important reductions on the observed figures are imperiously facing the exploration geochemist if he is to develop a valuable prospecting tool. A serious attempt is presently made to solve this problem.

References

1. Sylvain J Pirson, 1946, DISTURBING FACTORS IN GEOCHEMICAL PROSPECTING, Geophysics, Volume 11, Issue 3, pages 312-320, https://doi.org/10.1190/1.1437252. □