HGS Bulletin

Volume 61, Number 2

Houston Geological Society

October 2018

From the President
HGS - The Elephant in the Room

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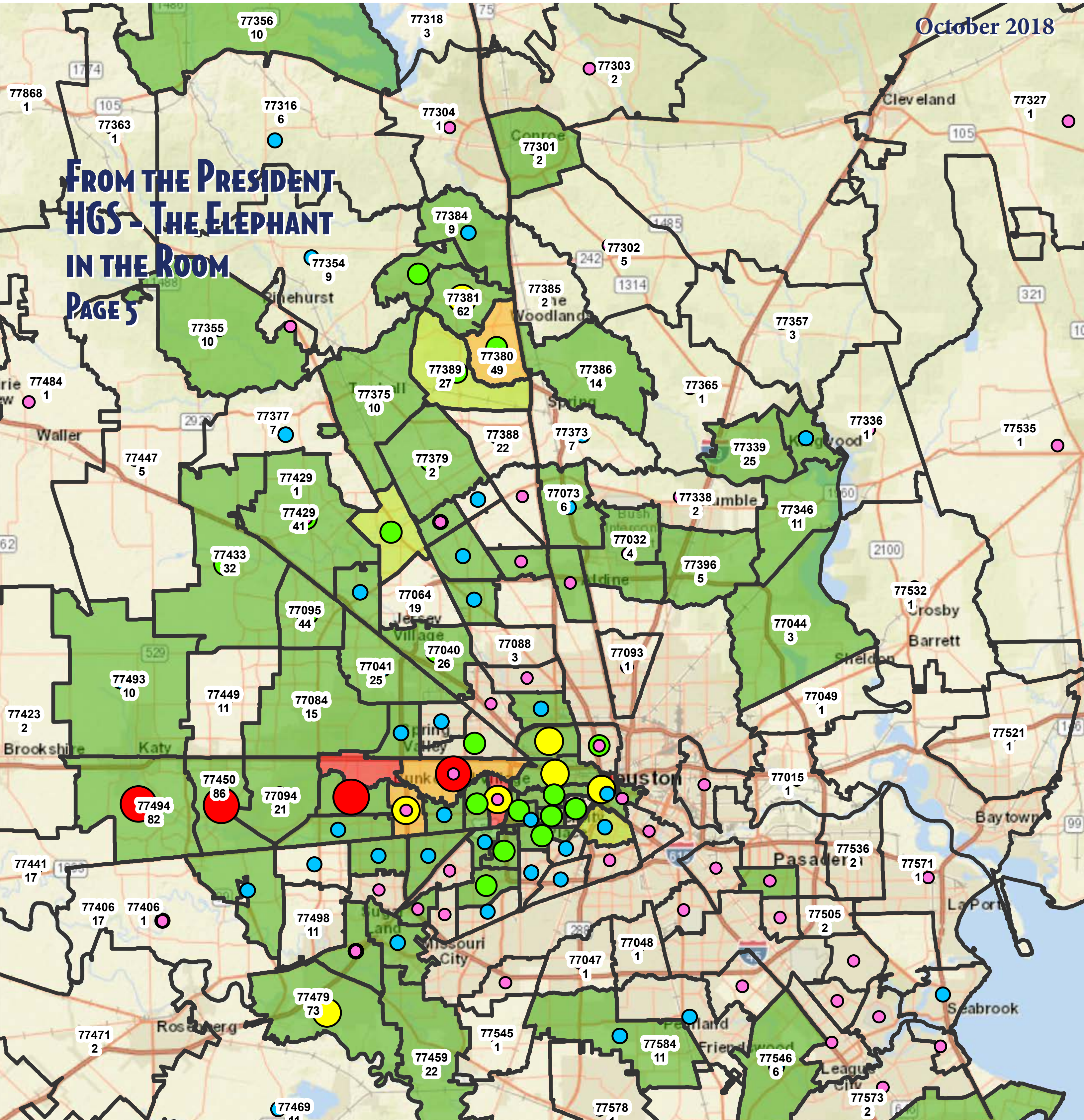

The Bulletin

Houston Geological Society

Volume 61, Number 2 — October 2018

In Every Issue

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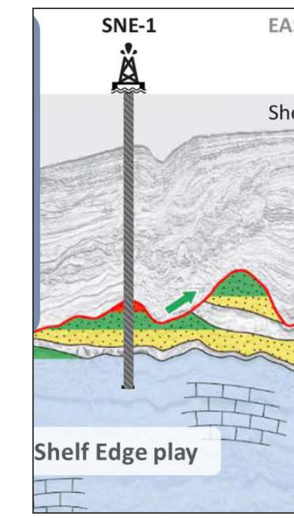

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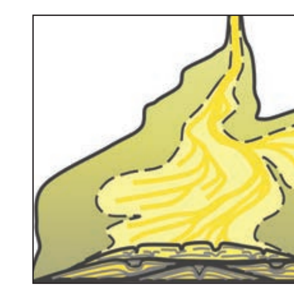

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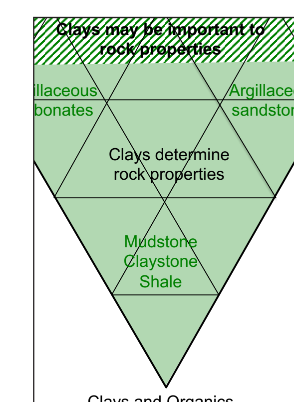

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EARTH SCIENCE WEEK

Earth Science Activities for the Whole Family Coming in October!

Earth Science Week, 2018
October 14 – 20

HGS in partnership with the American Geosciences Institute (AGI) is pleased to announce the theme of Earth Science Week 2018

Earth as Inspiration

This year's event emphasizes artistic expression as a unique, powerful opportunity for geoscience education and understanding in the 21st century.

In celebration of Earth Science Week Houston, HGS will be hosting the following exciting events:

Saturday, October 13 (11:00 am – 3:00 pm)

Earth Science Celebration at the Houston Museum of Natural Science
Our popular passport program guides students through hands-on activities and interactive science demonstrations.

Check in at Event Table in the Grand Hall before purchasing tickets.
Special pricing for the event: $3.50 K – 12 students
$3.50 College Students/Teachers/Professors with valid school/college ID
Teachers: 2018 ESW Toolkits free with valid school ID

Sunday, October 21 (12:00 pm – 3:00 pm)

Wiess Energy Hall Field Trip at the Houston Museum of Natural Science
4th Floor Duncan Family Wing
Step onto the Wiess Energy Hall drill floor to start your indoor fieldtrip adventure.
Journey from the Big Bang to the Houston of the future.

Check in at Event Table in the Grand Hall before purchasing tickets.
Special pricing for the event: $3.50 K – 12 students
$3.50 College Students/Teachers/Professors with valid school/college ID

For more information, see the HGS Earth Science Week webpage
https://www.hgs.org/earth-science-outreach

Cheryl Desforges
President@HGS.org

HGS – the *Elephant in the Room*

Hopefully, you all know HGS is the largest local Geological Society in the world, even with our currently diminished 3200 members. We are the "elephant in the room" when it comes to local societies!

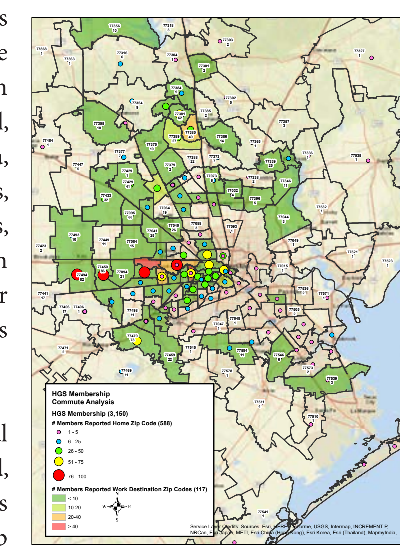
But we can only estimate by inference the percentage of all geologists in the Houston area belong to HGS.

- American Geosciences Institute (AGI) says there are 54,226 geoscience employees in the State of Texas, not including federal employees or self-employed (https://www.americangeosciences.org/policy/factsheet/states).
- The Texas Board of Professional Geoscientists (TBPG) says there are **4,065** licensed geoscientists in the State of Texas.
- By my inspection of the TBPG list based on zip codes indicates there are 1,011 licensed geoscientists in the greater Houston area. This is **25%** of the total licensed geoscientists in the State.
- If that same percentage, **25%**, is similar for the AGI total, there would be **at least 13,556 geoscientists in the Greater Houston area**. But because of the strong oil and gas presence, I suggest there may be more geoscientists in the Houston area.

All of a sudden, our "elephant in the room" looks more like the *pygmy elephant in the room.*

So, we HGS members need to ask ourselves, "Why don't many more geoscientists in the Houston area join our organization?" After all, we're already a very diverse group of geoscientists who ply our geoscience trade in a myriad of industries and subspecialties. Our members provide professional, scientific and technical services in oil and gas and other minerals, environmental, engineering geology, space science, academia, fundamental research, and many service areas, to name a few. And as one of our members, Mike Erpenbeck, once said, "I needed to join HGS, because where else can you get together with a group of other geoscientists and discuss what you love – geology!"

Possibly one reason we don't attract more local members is HGS is geographically challenged, because, even though our membership is located worldwide, most of our membership is widely distributed around the counties that are the Greater Houston metropolitan area. Harris County alone is 1,777 square miles. Historically, HGS membership was largely focused around downtown Houston. But over the years, even though our populations have primarily extended westward towards Katy and northward towards the Woodlands, we are still widely distributed (see attached map, complements of Tami Shannon). HGS has continued to adapt to these ever changing geographic distributions of our membership by having meetings, short courses, and other events spread around the greater Houston area. Events to keep our professional skills current include short courses, field trips, conferences, and of course our meetings – General Lunch and Dinner, International Explorationists, North American Explorationists, Northsiders, Environmental & Engineering Geology. We care about our community by participating in many activities – Science and Engineering Fair, Earth Science Week, Museum of Natural Science, and Educational Outreach. But geologists like to have fun. So we have many social events, including the Golf Tournament, the Saltwater Fishing Tournament, the Tennis Tournament, the Skeet Shoot, Outcrop Family Campout and of course our annual spring Shrimp Peel social event. We are now planning to take another step to serve our general membership and increase our membership by having a fall member and new member invitation social event. In particular we are planning ROCKTOBERFEST on October 20th at Watson's House of Ale micro-brewery in west Houston (https://www.hgs.org/civicrm/event/info?id=2048), as well as possibly one in The Woodlands. Please join us and invite all your friends and colleagues.



I hope you will find many events to join that are close to where you live and work. But of central importance to all of our events is the benefit of NETWORKING! Networking is one of those things that *more is better*. So, I'm challenging all HGS members to reach out to your colleagues and tell them about the services and values HGS provides, and invite them to events, and to join HGS. Personal invitations are the best way to get others involved. At $30/year dues which generally provides member discounts for events, HGS is the best professional value a geoscientist can have! ■

Jim Tucker
editor.hgs@hgs.org

Getting your Points Across

I recently took the opportunity to view and score posters at the AAPG Student Expo in Houston, and the AAPG Student Chapter Rice Industry Geoscience Series (RIGS) annual presentations.

Poster sessions have evolved during my career as an alternative way to present data and interpretations from the traditional oral presentation in a dark room with slides and video. This poster format allows discussion with the presenter(s), and the conversation can delve into details of interest to the observer, in addition to the story presented by the researcher about their data and interpretations. A much more personal seminar than possible in the traditional oral presentation format.

The posters keep getting better and better. And the slides in oral presentations often seem to be getting poorer and poorer. Back when there were drafting (later graphics) departments, the slide artwork was done by professionals who had defaults and rules for slides that were projected for viewing to support technical presentations. These guidelines could sometimes seem heavy-handed, but these pros knew what would work graphically, and were always correct. Now that folks often compose their slides a few inches from their eyes on a screen, it is easy to compose a slide that looks fine onscreen or on a report page, but is a hard-to-read image when projected. And report pages projected as slides without redrafting never communicate well. This is not a problem for geosciences only, as I have see poor slides in many public presentations of diverse topics and seminars.

We have challenges not shared by other professions. Well log information is a perennial challenge, as are seismic record sections (often without scales). Photomicrographs and other micro-information require clear careful labeling and scales. I have worked with IBA teams the past few years on their slides and communicating, and emphasize that they know the story they want to tell, and make their graphics support their story. One of the best "rules" came from guidelines published by the Oklahoma City Geological Society in the 1960s (if I recall correctly). Take your slide copy, and pin it on the wall. Move back the number of feet that your artwork is in inches in its larger dimension. If you cannot understand the slide, work on it some more. If your audience is squinting at your slide, then they are not listening to your story.

This month starts an occasional series of "Lessons from a Career". Submissions are invited, since we all have something useful we can share. Please send the text file to editor.hgs@hgs.org.

So, work on your slides, volunteer for something, and have a safe month. ■

Lessons from a Career

Early Lessons

After a number of years in grad school, waiting for the cycle to come around, I was fortunate to start with the North American Producing Division of the AtlanticRichfieldCompany (ARCO) in May 1978. The three month introductory training in Dallas for geologists did not start until September, so I was assigned to the geoscience research laboratory, also in Dallas. Walking in the first day, in my ill-fitting doubleknit suit, I was introduced to my new workgroup as "our new seismic stratigrapher". After looking around to see who was following me in, I figured I was going to need to quickly learn some geophysics, since I had avoided it in grad school.

Lesson: You never know what you will need to know, so you had better be prepared for anything.
ARCO was trying to figure out how we were going to do seismic stratigraphy, as AAPG Memoir 26 on seismic stratigraphy had recently been published, and we had lots of catching up to do. So, I studied Dobrin's book in the afternoons, and looked at sidewall cores in the mornings, and tried to see patterns in the corresponding well log data. I had some familiarity with elasticity and rock rheology from rock mechanics, so the basics of reflection seismology were not too hard. Looking at the 700-800 Gulf of Mexico sidewall cores stored at the lab was instructive, and I chewed up a lot of mudstone for grain size, learning a lot.

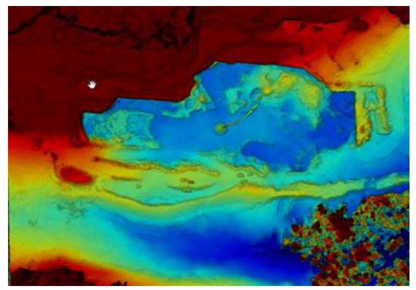
Early Lessons *continued on page 9*

The Houston Geological Society Continuing Education Committee Presents

Introduction to UAV (Drone) Aerial Surveys and Other Applications

Workflows and Demonstration

A Half-Day Short Course
by Mike Allison, Raptor Aerial Services LLC
Friday, October 26, 2018 • 11 am – 4 pm



The use of UAVs, unmanned aerial vehicles, or drones as they are more commonly referred to, is rapidly growing in many industries including oil and gas. The first drones were used for military purposes. Today, even though there are over 20,000 drones used by various armed forces worldwide, most drones are used for civilian purposes. In a recent report, the estimated number of Enterprise or Commercial-use drone shipments in 2016 was 110,000. This number will reach over 800,000 by 2021. Consumer drone shipments are expected to be around 29 million by 2021.

This overview course will cover types of drones, how drones work, and how they are being utilized to solve business problems in a more efficient, safer manner, and at a lower cost than traditional methods. Federal Aviation Administration (FAA) requirements and regulations for operating small unmanned aircraft (UAS) will also be covered. Data products with quantified operational use, generated from drone imagery, include: high-resolution aerial photos and videos; Orthomosaic (photo maps); Digital Surface elevation/Terrain Models (DSM, DTM); 3D models involving detailed measurements, such as Area, Volume, Length, Surface Profiles; and Infrastructure Inspections (optical zoom, thermal imaging). How drone data seamlessly integrates with other applications, such as Geographic Information Systems (GIS) will be discussed. Specific applications in flood control and surface mining will be demonstrated. Examples will be shown of other types of sensors being used on drones, including gas leak detection, air quality, Ground Penetrating Radar (GPR) and other geophysical applications. The last part of the course is hands-on, and will involve laying out and surveying Ground Control Points (GCPs) and flying drones to acquire small aerial surveys.

Pricing

HGS Member:	$65.00
HGS Student Member:	$45.00
Non-Member:	$105.00

Non-members can save $10 and receive the Member registration price IF they apply for any category of HGS membership online (https://www.hgs.org/membership_overview), submit the application, including payment, then register for the course by calling the HGS Office (713-463-9476) before receiving formal acceptance.

NO WALK-UPS ACCEPTED

Seating is limited to 30.

Registration: by 5 PM, Friday, October 12, 2018

Registrants wishing to participate in the Drone Field Demonstration should wear long pants and boots.

All Registrants should print and deliver the accompanying Waiver, signed, at check-in. Otherwise they will be required to fill in and sign a blank copy on the spot.

Notebook, Certificate of Attendance, Networking Lunch, and Refreshments are included in the Registration price.

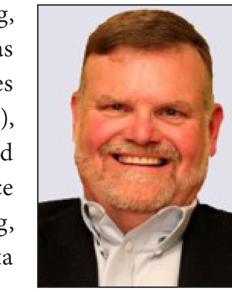
Doors open at 10:30 AM, Lunch begins 11 AM. Presentation and field exercises 12 Noon – 4 PM.

Date: Friday, October 26, 2018 • 11:00 am – 4:00 pm (Doors open at 10:30 am)
Location: Star Creek Ranch • 25801 Stockdick School Road, Katy, Texas 77493
(north of Clay Road and west of Highway 99)
Please make your reservations on-line through the Houston Geological Society website www.hgs.org
For more information about this event, contact HGS Office 713-463-9476 • office@hgs.org

Course Outline

- History of Drones
- UAV Growth & Industry Adoption
- FAA Rules for Operating a UAS
- Basic Components of a Drone System
- Types of Drones
- Drone Sensors
- Software
- Ground Control Points (GCPs)
- Drone Aerial Survey Workflow
- Photogrammetry and Elevation Modelling
- Drone Aerial Inspections
- Summary of Actionable Data Products from Drones
- Demos and Aerial Survey Field Exercises

Biographical Sketch



Mike Allison holds a BS and MS in Geology. He has 34 years of experience in the upstream oil & gas industry. Mike's experience and background in both Geoscience and IT make him uniquely qualified to recognize how technical solutions can solve E&P business problems. Much of Mike's experience has been focused on leading IT teams directly supporting key E&P departments including Geosciences, Engineering, Spatial/GIS, Land and SCADA. He has worked for different O&G companies including Majors (Gulf Oil and Chevron), Independents (Devon Energy and Fieldwood Energy) and several Service Companies (Exploration Logging, Landmark Graphics, Geoscience Data Management and Moblize).

After leaving Fieldwood Energy, he founded a drone services company named Raptor Aerial Services (RAS). His company provides aerial mapping surveys, stockpile volumetric calculations, inspections, data collection and marketing to a variety of industries. The company provides solutions focused on increasing sales, reducing costs, saving time and improving safety. RAS is fully insured and FAA Part 107 certified.

Mike is an active member of AAPG, HGS and SPE. He has severed as the Treasurer-Elect and Treasurer on the HGS Board. As a member of the HGS Continuing Education committee, he conceived and initiated the recording of HGS presentations now available at https://www.hgs.org/multimedia_overview. Last October, Mike taught an HGS Continuing Education Course entitled, "Introduction to Drones (UAVs) for Surveying in the Energy Business". He has made several presentations on the use of drones to various industry groups including the Montgomery County Extension Office, Energy Drone Coalition Summit & Expo, HGS Flood Conference, Society of Independent Professional Earth Scientists (SIPES) and the Texas Association of Environmental Professionals (TAEP).

Lessons From a Career continued from page 7

We were also looking at compaction in silicious rocks so I interpreted some 2D seismic lines in offshore Eugene Island where three wells crossed a sandy channel in a shaly-sandy channel-shaly cross-section in one interval. I was able to define a pronounced compaction anomaly over the channel, using a residual technique Dr. Nettleton showed us in undergraduate introduction to geophysics class.

Lesson: Some of the best ideas you will have may be early ones. After the three month training with three dozen other rookies, we all dispersed to districts, and two others and I went to Tulsa. This was not an active exploration district, but was an unbeatable place to start, with an abundance of well data, and a long history, and ARCO had lots of fee and held-by-production (HBP) acreage. Also there were five geologists with 30-35 years' experience, an unbelievable benefit.

There was lots of experience and lots of files full of data. You could find old linen maps listing "Indian Territory" in the title block, and old plane table sheets in the files. I had worked in the Ouachita Mountains in school, and never expected to use that experience again. However, ARCO and predecessor company Sinclair had blooms of interest in that trend every eight years or so, and a discovery in the Novaculite near Ardmore prompted us to look for opportunities, and we drilled a wildcat in SE Oklahoma to chase this play. Other experience in the Arkoma and Anadarko Basins was invaluable. The Oklahoma laws favored independents, so there were lots of forced-pooling applications to follow on all the company-interest legacy acreage. Lots of ideas and never enough time to chase them all.

Lesson: You will never beat the one-zone or one-county specialists, unless you have the same decades to master the subsurface that they did. ■ *(to be continued)*

HGS Golf Tournament

Monday – October 22, 2018
Sterling Country Club and
Houston National Golf Club
4-man Scramble

Come join us for golf, food, friends and fun at the annual HGS Golf Tournament at our new location, **Sterling Country Club** and **Houston National Golf Club** (www.sccathn.com). There will be prizes awarded for closest to the pin and long drive as well as many great door prizes for participants.

Entry Fee: $175.00/Golfer or $700.00/Team.
Early Bird Special: Sign up before September 25th to receive a discount of $25.00/Golfer or $100/Team.
Entry Deadline: October 17th.

Individual entries will be grouped with other individual golfers to make a foursome. Entries are limited to and will be accepted on a first-in basis.

Companies or individuals interested in sponsoring the event should contact Elliot Wall at 713-328-2674 or elliot.wall@corelab.com. *Sponsorship deadline is September 30th.*

SCHEDULE OF EVENTS

8:00 – 9:45 a.m.	Registration and free use of driving range and mini games, breakfast provided
10:00 a.m.	Shotgun start
3:00 p.m.	Cash bar, open buffet
3:30 p.m.	Door prizes and awards presentation

REGISTRATION OPTIONS
Online: www.hgs.org/golftournament
Email: office@hgs.org
Fax: 281-679-5504
Mail: Houston Geological Society, 14811 St. Mary's Lane, Suite 250, Houston, TX 77079
If paying by check, please make check payable to HGS Entertainment Fund.

Team Captain ____________________ Phone ________________ Amount Enclosed __________

Company ____________________________ Email ____________________________________

Billing Address ____

Credit card # ____ Exp. Date ________ Code# ________

Please Provide Email Addresses For All Team Members. All Communications Will Be Done Via Email.

Foursome Members *(Please Print)*	Company	Phone Number/Email	Hdcp/ Avg. Score
1. ____________	____________	____________	______
2. ____________	____________	____________	______
3. ____________	____________	____________	______
4. ____________	____________	____________	______

*Please provide email addresses for **all team members**. All communications will be done via email.*

HGS Golf Tournament

Monday – October 22, 2018
Sterling Country Club and
Houston National Golf Club

Sponsorship Application

Trevino Sponsorship $250.00
- **Sponsor Logo** signs on courses.
- **Company Name** displayed on sponsor recognition board at registration and awards banquet.
- **No Complimentary Registration**

Hogan Sponsorship $500.00
- **Sponsor logo** signs on courses.
- **Company logo** displayed on sponsor recognition board at registration and awards banquet.
- **1 Complimentary Registration**

Nicklaus Sponsorship $1,000.00
- **Sponsor Logo** signs on courses.
- **Company Logo prominently** displayed on sponsor recognition board at registration and awards banquet.
- **Company logo** displayed on driving range and practice putting green signs.
- **2 Complimentary Registrations**

Title Sponsorship $2,000.00
- **Sponsor logo** signs on courses.
- **Company logo prominently** displayed on sponsor recognition board at registration and awards banquet.
- **Company logo** displayed on driving range and practice putting green signs.
- **Company logo** displayed on beverage carts.
- **Sponsorship includes tournament entry for one team (4 people).**

SPONSORSHIP REGISTRATION OPTIONS – Deadline October 15
Online: www.hgs.org/golftournament
Email: office@hgs.org
Fax: 281-679-5504
Mail: Houston Geological Society, 14811 St. Mary's Lane, Suite 250, Houston, TX 77079
If paying by check, please make check payable to HGS Entertainment Fund.

Name ________________________ Phone ________________ Amount Enclosed __________

Company ____________________________ Email ____________________________________

Billing Address ____

Credit card # ____

Exp. Date ________ Security Code# ________

Please email your company logo to office@hgs.org and elliot.wall@corelab.com.
Note: Company logos (high resolution file) must be received no later than September 30th.
If there are any questions, please contact Elliot Wall at 713-328-2674.

Monday, October 8, 2018

Joint HGS and GSH Dinner Meeting

Live Oak Room • Norris Conference Center • 816 Town and Country Blvd #210
Social Hour 5:30–6:30 p.m.
Dinner 6:30–7:30 p.m.

Cost: $40 Preregistered members; $45 non-members/walk-ups

To guarantee a seat, pre-register on the HGS website & pre-pay by credit card.
Pre-registration without payment will not be accepted.
Walk-ups may pay at the door if extra seats are available.

If you are an Active or Associate Member who is unemployed and would like to attend this meeting, please call the HGS office for a discounted registration cost. We are also seeking members to volunteer at the registration desk for this and other events.

Igor Effimoff and Jon Keall
FAR Limited

SNE and FAN World Class Discoveries Offshore Senegal Herald a Major New Hydrocarbon Province

Historically, interest in MSGBC (Mauritania-Senegal-Gambia-Bissau-Conakry) had been limited and Senegal had been largely overlooked.

In early 2006, FAR Limited acquired an interest from then operator Hunt Oil in the Rufisque Offshore, Sangomar Offshore and Sangomar Deep Offshore blocks in Senegal. A large 2000km2 3D seismic survey was acquired but Hunt Oil exited the area shortly thereafter, leaving FAR as operator with 90% equity along with Petrosen, the national oil company of Senegal (10%).

In 2012, a detailed mapping and prospect generation exercise was carried out by FAR, resulting in an updated prospect and lead portfolio, which was taken to the farm-out market. Farm-out deals were concluded with Cairn Energy (operator; 40%), ConocoPhillips (35%), FAR retaining 15% and Petrosen 10%.

Two initial exploratory wells were drilled, back to back, on two separate plays in 2014. FAN-1, the first ever deepwater well in Senegal was drilled in 1,427m water depth, targeting stacked Cretaceous sandstone reservoirs in stratigraphic traps. The well was drilled to a total depth of 4927m with excellent oil indications over a vertical interval of over 500m and no oil-water contacts encountered. Several distinct oil types were sampled ranging from 28° API to 41° API. The main reservoir sections are thinly bedded, yielding approximately 29m of net oil pay in Albian sandstones. The FAN-1 discovery is larger than the pre-drill estimate and audited 2C recoverable resources are 198mmbbls. In addition to discovering oil, FAN-1 encountered a thick interval of excellent quality oil-prone source rocks.

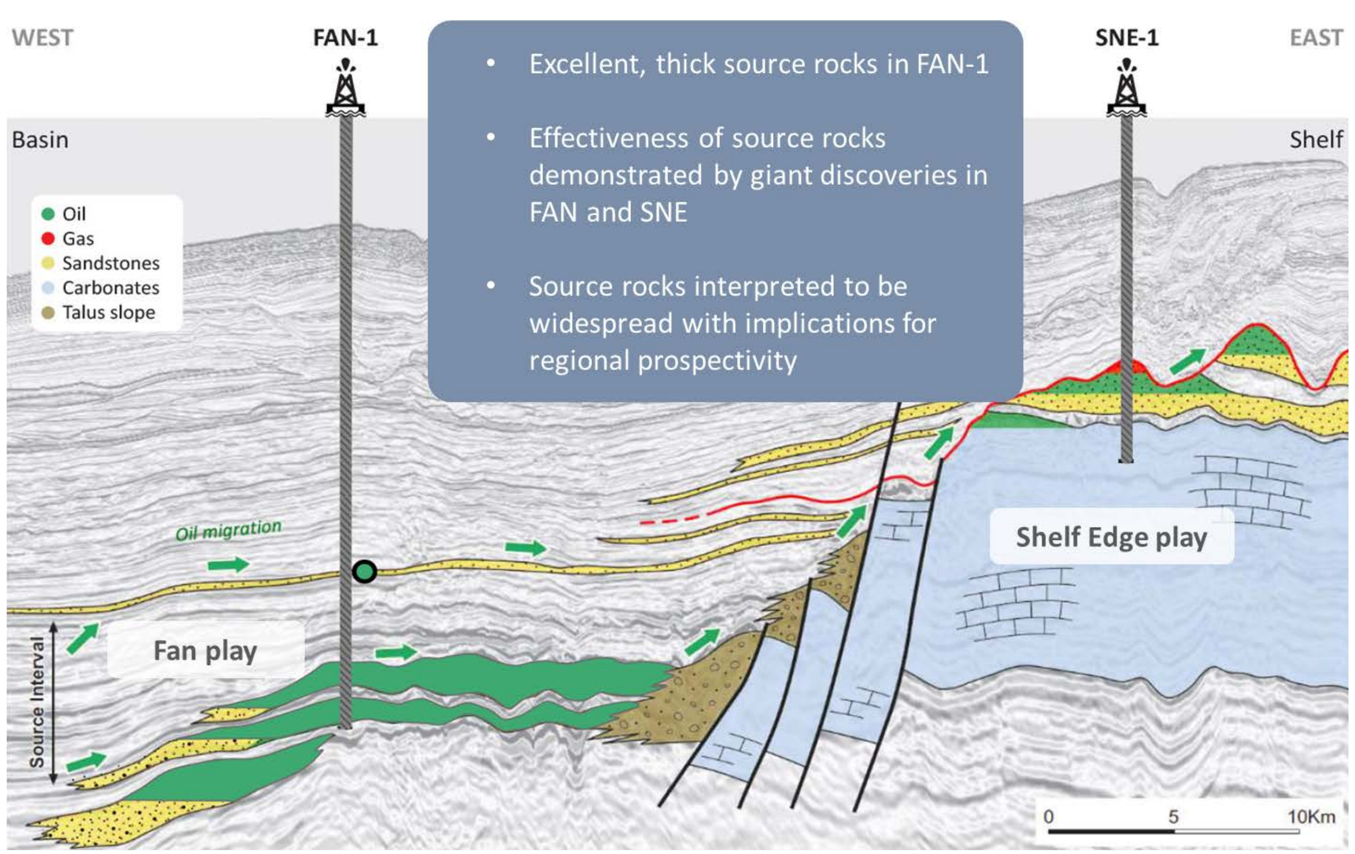


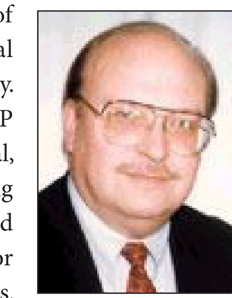
Figure 1. *SNE Field geological setting and discovery well*

SNE-1 in 1,100m water depth, was drilled to a total depth of ~3,000m. The well targeted Cretaceous sandstone reservoirs in a combined structural and stratigraphic trap. Oil and gas were encountered at the primary objective in excellent quality Albian sandstones with a gross 96m oil column and net oil pay of 36m. High quality 32° API oil was sampled, together with gas and water. Early appraisal results confirmed the continuity of the main oil and gas columns and a DST of the first appraisal well (SNE-2) flowed oil at a constrained rate of 8000mmbbls per day. Audited 2C recoverable resources are 641mmbbls. These figures are about four-fold larger than the pre-drill estimate.

A second FAN type feature was successfully drilled by FAN South-1. As such, a total of eleven wells have been drilled on the blocks, all of which encountered hydrocarbons. First oil from SNE is expected between 2021 and 2023.

The story is evolving but these exceptional exploration results have confirmed the Senegal offshore as a new major oil province. ■

Biographical Sketch



Igor Effimoff has over 45 years of upstream technical and managerial experience internationally and domestically. He is founder and principal of E&P Consulting, a firm providing geological, geophysical and engineering consulting services to evaluate investment and business development opportunities for various international and domestic clients. FAR has been a client since 2005. Previously, Dr. Effimoff served as Chief Operating Officer for Teton Petroleum Company from 2002 through 2005 and President of Pennzoil Caspian Corporation from 1996 through 2001. He served on the board of Harvest Natural Resources, Inc. and TruStar Petroleum Corporation, as well as several nonprofit boards. He started his career with Shell Oil.

Dr. Effimoff has a doctorate degree in geology from the University of Cincinnati and is a graduate of the Harvard Business School Advanced Management Program. He is a fellow of the American Association of Petroleum Geology, Geological Society of America, Society of Exploration Geophysicists, Society of Petroleum Engineers and the Houston Geological Society.

Wednesday, October 10, 2018

HGS Environmental & Engineering Dinner Meeting

Black Lab Pub, Churchill Room • 4100 Montrose Blvd.
Social Hour 5:30–6:30 p.m.
Dinner 6:30–7:30 p.m.

Cost: $30 Preregistered members; $35 non-members/walk-ups

To guarantee a seat, pre-register on the HGS website & pre-pay by credit card.
Pre-registration without payment will not be accepted.
Walk-ups may pay at the door if extra seats are available.

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Glenn Lowenstein, PG
Terrain Solutions, Inc.

Protecting the Geoscience License that Protects Texas and Texans

The Texas Sunset Commission wants to abolish the Geoscience license. Look at todayís headlines. Environmental issues are often in the top 10 lists of voterís concerns. To say that the environment is not important to merit assessment by government licensed professionals or that geoscience is not used in the evaluation of the environment is not correct. My company, Terrain Solutions, often finds itself privy to information about unreported adverse environmental conditions which has not even entered the radar of environmental regulatory agencies. Geoscientists serve on the front lines to protect an uneducated public from the dangers. To say that the current manpower of regulatory bodies can adequately address all the environmental concerns, undervalues the importance of environmental assessment. Every additional educated and trained body is needed in the environmental arena from safe drinking water identification to risk assessment of chemical releases.

Understanding the history of how we convinced a group of independent-minded geoscientists to accept governmental oversight is complex. Efforts towards Texas geoscience licensure failed in the 1980s and was resurrected to become a Geoscience Act in 2001 and a funded board in 2003. I will give my version of the road that brought us the Sunset report, a look towards consequences of the return to pre-licensure, what we can do to improve enforcement, continuing education, and the ethics of our profession to improve licensure, and ultimately, why we believe licensure is good for all geoscientists and critical for the future of Texas. ■

Biographical Sketch

Mr. Glenn Lowenstein, P.G., C.A.P.M., is the President of Terrain Solutions, Inc., an environmental consulting company based in Houston, Texas. Mr. Lowenstein holds a BS in Geology from Queens College and a MS in Geology from Texas A&M University, College Station, Texas. He is a Licensed Professional Geologist (P.G. # 28) in the State of Texas and is a Corrective Action Project Manager (CAPM # 116). Mr. Lowenstein has over 25 years of professional experience in environmental and geological applications which include environmental site assessments, UST investigations, and geologic studies of surface faults. He has performed environmental site assessments for both public and private sector projects. Mr. Lowenstein served as a Professional Member on the Texas Professional Geoscience Board from 2005-2011.

Monday, October 22, 2018

HGS North American Dinner Meeting

Live Oak Room • Norris Conference Center • 816 Town and Country Blvd #210
Social Hour 5:30–6:30 p.m.
Dinner 6:30–7:30 p.m.

Cost: $40 Preregistered members; $45 non-members/walk-ups

To guarantee a seat, pre-register on the HGS website & pre-pay by credit card.
Pre-registration without payment will not be accepted.
Walk-ups may pay at the door if extra seats are available.

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Steve Tobias
NearFX LLC

Applying New Technologies to Old Areas: Relative Geologic Time, Wheeler Diagrams and Near Field Exploration in Faulted Plays

Large 3D seismic volumes cost tens of millions of dollars to acquire, millions to process and hundreds of thousands or more to interpret. And yet more often than not, only a small percentage of seismic reflections are mapped out, typically top/ base of key reservoirs and seals, flooding surfaces and sequence boundaries. It seems intuitively obvious that a lot of useful information is being left behind, and yet what to do? Picking every horizon would be as de-focusing as it would be time consuming. And anyway, what would it give you?

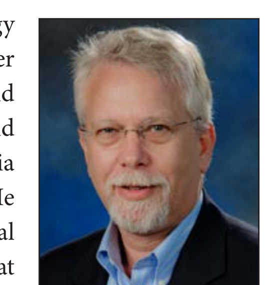
This presentation explores this intriguing topic by examining an integrated data set offshore Louisiana. Using new technologies, every peak and trough in a 3D volume can now be rapidly converted into thousands of small "mini-maps" which are then weaved into a highly detailed volume by an interpreter. Because these many thousands of surfaces are chronostratigraphic, it becomes possible for the first time to assign a Relative Geologic Time (RGT) to each one of them using quite clever software (several excellent vendors offer RGT capability – here we use Paleoscan by Eliis). This allows the ready transformation of these richly detailed seismic volumes from a form familiar to workstation users (the vertical axis being depth or two-way-time) into something totally unique: a vertical RGT axis. This transformation yields the 21st century version of the venerable Wheeler diagram, but with exquisite 3D detail instead of a cartoon-like representation. This transform should be every bit as important to a seismic interpreter as a Fourier or Wavelet Transform is to a geophysicist. Yet because of its newness, the application of Wheeler Transforms to interpretation methodology is in its infancy.

With the help of:1) the Wheeler Transform, 2) viewing in different azimuths, 3) integrating and propagating well logs and paleo tops, 4) studying the "instantaneous" accommodation space of each sequence, and 5) the construction of key seismic attributes and animation techniques, the weaved RGT volume can be sectioned into properly defined stratigraphic sequences. Only then can stratigraphic exploration proceed in a systematic way while fully integrating all the 3D seismic data.

What is perhaps just as interesting for teams working the Gulf of Mexico is that this approach provides an important new seismic stratigraphy tool for those exploring in faulted environments. Many must have noticed that the eustatic signatures so helpful to international seismic stratigraphers (such as onlap, downlap, etc.) are mostly missing in and around expansion faults. The reason for this is that the various onlaps terminate against fault planes instead of underlying strata. The eustatic signatures are there, but manifest in a different dimension. Only through the study of expansion profiles can these signatures be recovered and various systems tracts better described. As will be discussed, the study of expansion profiles dovetails quite well with RGT analyses. Another important part of this workflow that will be discussed is the need to initially decouple structural from stratigraphic analysis, and then recouple them again within the geomodel, followed by the propagation of various calibrated properties throughout the model.

Taken together, these new technologies hold the promise to rejuvenate "Near-Field" stratigraphic exploration in old areas. ■

Biographical Sketch



Steve Tobias holds degrees in geology and geophysics and has had a long career in both New Ventures and Near Field Exploration. He started with Mobil, and later worked with Tenneco in Colombia and BHP Petroleum in Australia. He was Pogo Producing's first international exploration manager during the time that they drilled up the highly prolific Gulf of

HGS North American Dinner *continued on page 17*

Wednesday, October 24, 2018

Petroleum Club of Houston • 1201 Louisiana (Total Building)
Social Hour 11:15 a.m.
Luncheon 11:45 a.m.

Cost: $35 Preregistered members; $40 non-members/walk-ups

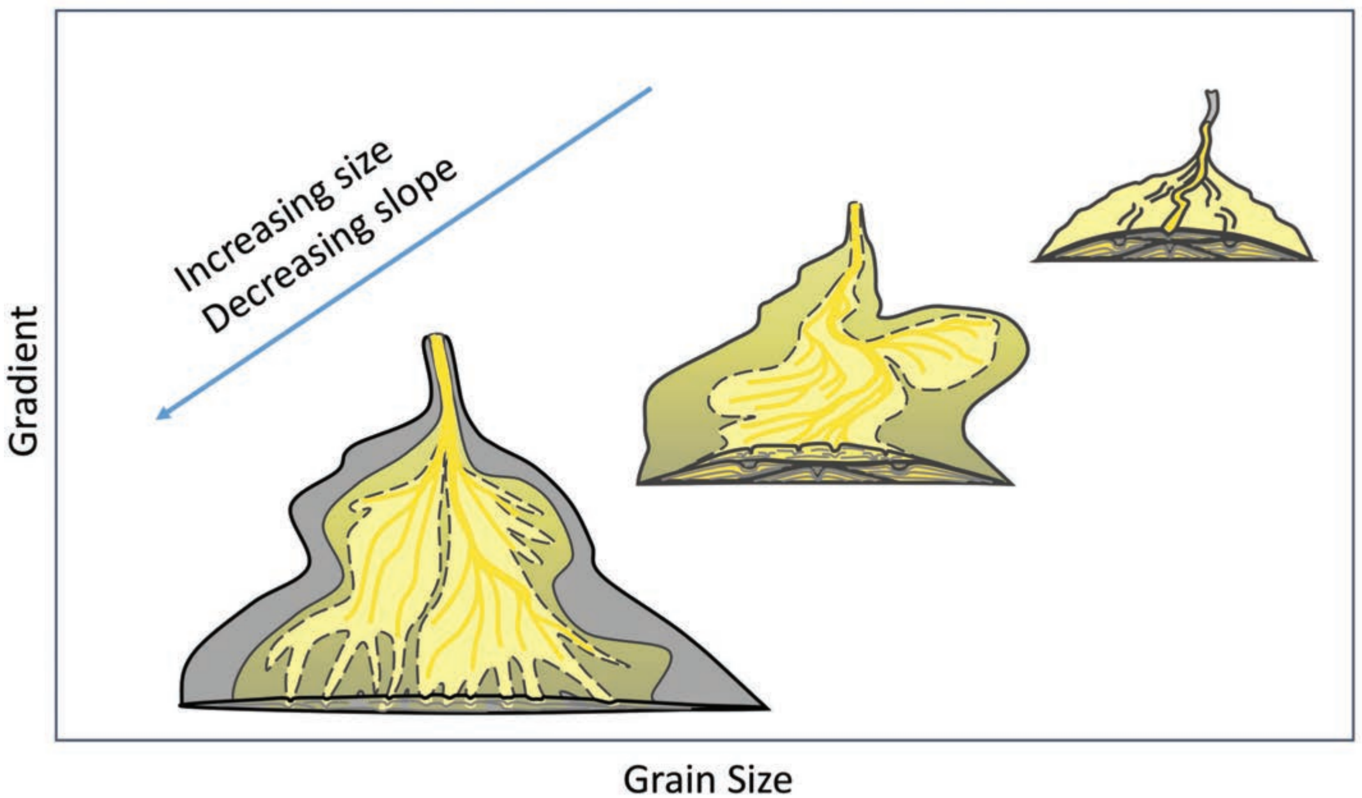
To guarantee a seat, pre-register on the HGS website & pre-pay by credit card.
Pre-registration without payment will not be accepted.
Walk-ups may pay at the door if extra seats are available.

If you are an Active or Associate Member who is unemployed and would like to attend this meeting, please call the HGS office for a discounted registration cost. We are also seeking members to volunteer at the registration desk for this and other events.

HGS General Luncheon Meeting

David Hoyal, Timothy Demko, Juan Fedele and Gwladys Gaillot
ExxonMobil

Deep-Water Process Stratigraphy



Supercritical-Transcritical-Subcritical Submarine Fans with different reservoir properties and stratigraphic trap potential

Models of deepwater stratigraphy have stressed the importance of changes in accommodation. While accommodation is a necessary condition for the long-term preservation of deepwater deposits, actual depositional processes are more complicated, involving complex interactions between gravity currents and evolving basin topography induced by intrinsic mechanisms or extrinsic forcing.

Deepwater channel and lobe organization evident in seismic data are strongly related to gradient, and are characterized by morphodynamic successions, distinctive patterns of vertical successions that can be recognized in cores and/or well logs. Deepwater process stratigraphy is the extension of sequence stratigraphy to include constraints introduced by understanding the interactions between gradient, and the physics of fluid flow, sediment transport, erosion and deposition. This process-based understanding is derived from integrated studies of physical experiments, numerical models, interpretation of high-resolution seismic data sets, observations of modern seafloor environments and processes, and outcrop studies.

Process stratigraphy is important at all scales of geologic characterization from understanding basin fill and play element distribution during petroleum exploration, to describing and predicting reservoir, seal, reservoir quality, and connectivity in development and production. At the basin scale, extrinsic controls on basin gradient include the tectonic regime, sediment delivery from the catchment, and along-continent transport by ocean currents. The gradient also intrinsically evolves as a result of sedimentation by turbidity currents. These processes operate at vastly different timescales. ■

Biographical Sketches

David Hoyal, a research geoscientist at ExxonMobil Upstream Research has over 20 years experience developing and applying process sedimentology/stratigraphy ideas in clastic stratigraphy. Dave initiated the first in-house experimental tank program at ExxonMobil URC circa 2000 and the program remains active. He developed innovative experimental techniques for modeling deltas and deep-water fans that have significantly improved our understanding of distributary system morphodynamics and stratigraphy. Dave is currently technical team lead of the Process Stratigraphy group at URC which applies concepts derived by integrating experiments, numerical models, seismic and outcrop to deep water reservoir prediction.

Tim Demko is currently a Senior Research Advisor at ExxonMobil Upstream Research Company in Houston, TX, with specialties in the sedimentology and stratigraphy of siliciclastic rocks. He received his BS in Geosciences from Penn State in 1983, his MS in Geology from Auburn in 1990, and a PhD in Geosciences from the University of Arizona in 1995. Tim was a mining geologist for P and N Coal Company from 1984 to 1988. He was a Postdoctoral Fellow at Colorado State University from 1994 to 1996, before joining Exxon Production Research in Houston, TX in 1996. At Exxon, and then ExxonMobil, Tim worked as a research geologist on fluvial sequence stratigraphy, and applied these concepts during foreign assignments with Imperial Oil in Calgary, Alberta Canada, and then seconded to Shell UK in London, England. After an assignment with ExxonMobil Production Nigeria back in Houston, Tim left the industry to join the faculty of the Department of Geosciences at the University of Minnesota Duluth, from 2002 to 2006. In 2007, Tim returned to the oil and gas industry, to ExxonMobil Exploration Company back in Houston. He joined ExxonMobil Upstream Research Company in 2009, and is currently working on the Process Stratigraphy of deepwater deposits. Tim lives in The Woodlands, TX with his wife Laura and their son, Noah.

Juan Jose Fedele has joined the Process Stratigraphy team at ExxonMobil bringing his experience in theoretical and experimental hydraulics, fluid mechanics, and sediment transport, with particular emphasis in gravity and open-channel flows and the mechanics of bedforms. Juan has worked experimentally on the development of new understanding of deepwater bedforms, their stability fields, and their application as recognition elements for flow conditions and environments of deposition.

Gwladys Gaillot, a Deep Water stratigrapher at ExxonMobil with 10 years' experience in development/production and research projects. Gwladys obtained a PhD in 2004 at the University of Montpellier, France from a study focused on the Modern Zaire Submarine Fan in collaboration with Total. She joined the Oil & Gas industry after a 2 years post-doctoral study of Gas Hydrates in the Nankai Trough with the Japanese Oceanographic Institute, Jamstec in Yokohama. In ExxonMobil, Gwladys worked as a seismic interpreter specialized in Deep Water Stratigraphy developing opportunities for various West African assets. She later joined the Process Stratigraphy team in the Upstream Research Company (URC) to develop updated depositional models of submarine fans that incorporate an autogenic process understanding.

HGS North American Dinner continued from page 15

Thailand. Steve led an international consulting group for seven years, and then co-founded South Bay Resources in 2003. It was extremely successful in using neural networks in the exploration of onshore Texas and Alberta, until it wasn't. Steve then joined Hess where he served in various roles, including Manager of Exploration Excellence and Denmark Exploration manager for three years. For the past year, Steve has provided exploration services for a variety of clients in the GOM and the North Sea. His current area of focus is offshore Gulf of Mexico on the outer shelf and deep water, with emphasis on subsalt plays. Steve also consults in the use of Paleoscan workflows.

October 2018 GeoEvents

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	1 **Don't wait, make your reservations online at hgs.org**	2 **HGS Board Meeting** *6 p.m.*	3	4	5	6
7	8 **Joint HGS/GSH Dinner Meeting** *"SNE and FAN World Class Discoveries Offshore Senegal Herald a Major New Hydrocarbon Province," Igor Effimoff and Jon Keall, Page 12*	9	10 **HGS Environmental & Engineering Dinner Meeting** *"Protecting the Geoscience License that Protects Texas and Texans," Glenn Lowenstein Page 14*	11	12 **GSH/HGS Saltwater Tournament** *TopWater Grill Marina, San Leon TX Page 20*	13 **Earth Science Week Earth Science Celebration at the Houston Museum of Natural Science** *Page 4*
14	15	16 **SPE Semi-Annual Gulf Coast Section Hiring Event** **Northsiders Luncheon Meeting** *Tentative -TBA*	17	18	19	20 **Energy Day** **First Annual HGS Rocktober Fest** *Watson's House of Ale 14656 Grisby Rd. Houston*
21 **Earth Science Week Wiess Energy Hall Field Trip at the Houston Museum of Natural Science** *Page 4*	22 **HGS Golf Tournament** *Sterling Country Club and Houston National Golf Club, Page 10* **HGS North American Dinner Meeting** *"Applying New Technologies to Old Areas," Steve Tobias, Page 15*	23	24 **HGS General Luncheon Meeting** *"Deep-Water Process Stratigraphy," David Hoyal, Timothy Demko, Juan Fedele and Gwladys Gaillot Page 16*	25	26 **HGS Continuing Education Introduction to UAV (Drone) Aerial Surveys and Other Applications** *Mike Allison Page 8*	27
28	29	30 **Machine Learning Essentials for Seismic Interpretation** *Live Webinar, Dr. Tom Smith Page 22*	31			

Reservations:
The HGS prefers that you make your reservations on-line through the HGS website at www.hgs.org. If you have no Internet access, you can e-mail office@hgs.org, or call the office at 713-463-9476. **Reservations for HGS meetings must be made or cancelled by the date shown on the HGS Website calendar, normally that is 24 hours before hand or on the last business day before the event**. If you make your reservation on the Website or by email, an email confirmation will be sent to you. If you do not receive a confirmation, check with the Webmaster@hgs.org. Once the meals are ordered and name tags and lists are prepared, no more reservations can be added even if they are sent. **No-shows will be billed.**

Members Pre-registered Prices:

Dinner Meetings members	$40
Emeritus/Honorary members	$40
Student members	$10
Nonmembers & walk-ups	$45
Except - Env. & Eng.	$30
Nonmembers & walk-ups	$35
Emeritus/Honorary members	$15

October 14 – 19, 2018
SEG 2018 Annual Meeting
Anaheim, California, USA

November 4 – 7, 2018
AAPG 2018 International Conference & Exhibition
Cape Town, South Africa

March 23 – 31, 2019
Explore the Solitario Flatirons with HGS Fieldtrip
Big Bend Ranch State Park

May 19 – 22, 2019
AAPG 2019 Annual Convention & Exhibition
San Antonio, Texas, USA

July 22 – 24, 2019
Unconventional Resources Technology Conference (URTeC 2019)
Denver, Colorado

GSH / HGS 18th ANNUAL SALTWATER TOURNAMENT

- Friday, October 12, 2018 -

TopWater Grill Marina, 815 Avenue O, San Leon, TX

Galveston Bay Complex and Offshore

We are looking forward to a big event this fall and we encourage full family participation!

Galveston Bay Complex Division

Trophies will be awarded for the heaviest individual Redfish (Non-Tagged), Speckled Trout, and Flounder. Trophies will also be awarded for the heaviest individual Stringer - 1 Redfish, 3 Speckled Trout, and 1 Flounder.

Galveston Offshore Division

Trophies will be awarded for the heaviest individual Ling, King Mackerel, and Mahi-mahi

REGISTRATION OPTIONS

- **Registration** fee of $75 includes: Launch Fee, Refreshments, Seafood Dinner after weigh-in, Trophies, and Door Prizes.
- **Registration on a Guided Boat** for 4 hours in the morning or mid-day is $225. Bait & tackle is included. Check with the GSH Office, 281-741-1624, for times and availability.
- Non-fishing friends and family enjoy a **Seafood Dinner** for $20

For more information, please contact:

Bobby Perez — Cell: 281-787-2106, Home: 281-495-8695, E-mail: rdphtx@gmail.com

Nathan Lenz — Cell: 281-468-5459, Office: 713 576 3371, E-mail: nathaniel.lenz@tgs.com

The Geophysical Society of Houston and the Houston Geological Society are non-profit and not-for-profit organizations serving the Geosciences Community. Corporate and individual contributions are appreciated and will be acknowledged on several sponsor boards and banners at the Weigh-In Station and Marina. All contributors will be recognized in the GSH Journal following the tournament. This is a great way to entertain friends, family, business associates, and clients. So spread the word!

GSH / HGS SALTWATER TOURNAMENT

NAME: ______________________ COMPANY: ______________________

ADDRESS: ____

PHONE: (B) ______________ (C) ______________ ______________

E-MAIL ADDRESS: ____

Upon receipt of the Registration form, each participant will be provided with a copy of the specific tournament itinerary and rules sheet by e-mail. Please **REGISTER EARLY!**

Please return this form with your check payable to: GSH SALTWATER TOURNAMENT and Mail to:

Geophysical Society of Houston (GSH), 14811 Saint Mary's Lane, Suite 204 • Houston, Texas 77079

Registration Fee: $ ________ + Sponsor Contribution: $ ________ = TOTAL $ ________

OR call the GSH office with Credit Card payment at: 281-741-1624

DISCLAIMER:

I acknowledge that the Geophysical Society of Houston will not be held responsible for injuries or accidents during this event.

PRACTICE SAFETY!!!!! Signature: ______________________

Africa Conference September 10-12, 2018

The annual HGS-PESGB Africa Conference was held September 11-12, 2018 at the Norris Conference Center in Houston drawing nearly 300 attendees from across the world. The meeting began Monday with a one day workshop "African Margin Petroleum Systems Seismic Workshop" led by Paul Bellingham, Ken McDermott and Lisa Fullerton from ION E&P Advisors and Neil Hodgson and Kayrna Rodriguez of Spectrum. Over 60 people attended the workshop that evaluated known and future petroleum potential along the African margin covering the Sirte, Congo/Kwanza, Rovuma and Somali Basins. Attendees were given seismic data from various basins to interpret and discuss the petroleum system potential, play types observed and what opportunities may remain in the basin.

Figure 1. *Conference Committee (L-R) William Dixon, Brian Horn, Phil Towle and Paul Haryott.*

The conference program began on Tuesday with the keynote speaker Tim O'Hanlon, Vice President Tullow Oil who addressed the forum about what the future potential could be for exploration in Africa. A complete 2 day program, included speakers from industry and academia and comprised 27 talks and 28 posters on a diverse and broad range of topics covering exploration strategies and exploitation projects across Africa. The technical program gave attendees a great overview of many of the petroleum producing basins in Africa and provided insights in to the latest geological concepts, strategies and techniques being used to unlock Africa's vast petroleum resources.

Figure 2. *Jerry Kepes addresses the lunchtime forum and roundtable*

Also included, for the first time this year, was a lunchtime panel roundtable discussion. The subject of this event was "Exploration in Africa, Past, Present and Future – Keys to Exploration Success and Disaster Avoidance" and featured current and former senior executives from the most active exploration companies in Africa including Anadarko, Kosmos and Tullow. This lively and stimulating debate, open to all conference attendees, provided insights in to recently successful exploration strategies and discussed future opportunities and challenges.

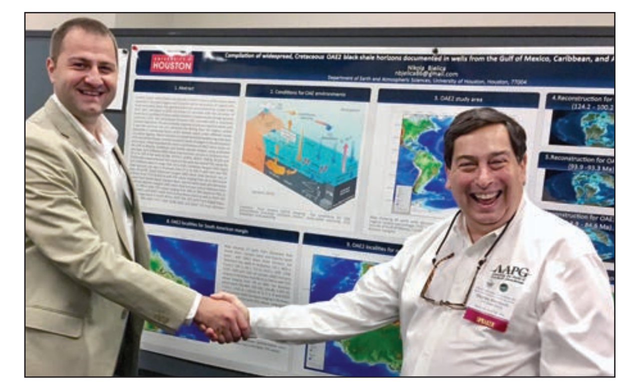


Figure 3. *Charles Sternbach with student poster presenter Nikola Bjelica from the University of Houston*

The exhibition hall had 27 vendors that provided great opportunities for attendees to evaluate new technologies and opportunities in Africa, while networking with old and new colleagues and associates alike.

Awards were made to:

Best Student Poster: Marcus Zinneker, et al, - University of Houston; "Plate Tectonic Framework for Petroleum Systems of the Atlantic Conjugate Margins: Northwest Africa-Eastern USA and Northeast South America-Equatorial West Africa".

Best Professional Poster: Rao Yalamanchili, et al, - CGG Multi-Physics; "Hidden Boundary Fault at East African Rift Basin Revealed with FALCON Airborne Gravity Gradiometry Data".

Best Paper: Monica Miley, et al, - Anadarko Petroleum: Reservoir Modeling of a deep-Water West African Reservoir: A Fully Integrated, Multi-Scenario Approach".

Figure 4. *Student Poster awardees -*

Rules for Clays: Tools for Understanding Rock Histories

By Stephen R. Schutter

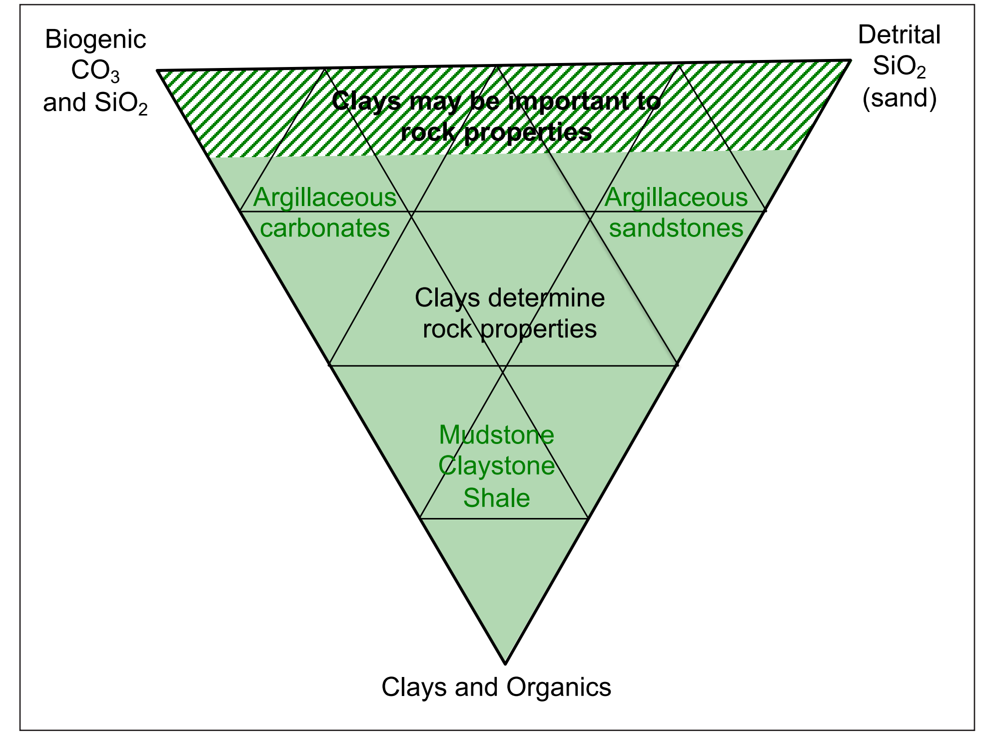


Figure 1. *In most sediments, clays determine the rock properties, both in terms of physical (particularly porosity, permeability, and compressibility) and geochemical characteristics. Only very clean and well-sorted coarse siliciclastics and carbonates are exceptions, and even then clays may occlude porosity.*

Clays get no respect. They are nearly ubiquitous in sediments, and are significant factors in determining rock properties (especially porosity), yet many geoscientists go no farther than referring to generic "clays". This short-changes the vast potential for more information on depositional environments and diagenetic history (and thus on petrophysics and engineering properties). Clays are not all the same; how and why they vary permits modeling sedimentary properties and predicting vertical and lateral variability, as well as understanding basin evolution. Clay suites can vary abruptly, and the properties of the various clays present may also be useful. Clays offer new and different opportunities for understanding rocks, many that aren't available through more conventional analysis.

The "hows" and "whys" of clay qualities and distribution can be expressed as a series of principles (rules) for understanding their depositional and diagenetic histories. These are basic principles, which should be considered when clays are considered, modified by local details (and sometimes unanticipated events). Through these basic rules, and how they may be modified, it is possible to understand the history of the clays, and develop models for their relationships.

Notably, clays are not directly related to the biologic/paleontologic processes of deposition, or to the redox condition of the sediments. Thus, they provide an independent record of the depositional processes, and a different set of variables for interpretation.

Clays not only yield information on deposition and diagenesis, but also provide valuable input for interpreting paleoclimate, sequence stratigraphy, structural interpretation, petrophysical properties, well engineering, and basin modeling. In addition to physical sedimentology and paleontology, study of the clays represents one of the principal ways to understand mudstones and their context.

While systematic analysis of clays is preferable, even the assessment of clays in existing plays (such as the Eagle Ford and the Permian Basin, illustrated below) can lead to new insights and new lines of exploration and development. Recognizing the variation in clays also helps to avoid potential pitfalls in the analysis of diagenesis and petrophysical parameters.

Technical Article *continued on page 25*

 continued from page 23

Introduction

Most geologists avoid thinking about clays, possibly believing that clays are very complex and because they really don't understand them. Clay analyses are treated as "whatever"; there is no expectation about which clays should be found. There seems to be a belief that there is a generic "clay" – that one clay suite is essentially like another, homogenized by depositional processes. Clays are also avoided because there is little general knowledge; many geologists are wary of being blindsided by "gotcha" revelations.

In reality, clays are much more than opaque chemical formulas and arcane structures. They may vary significantly, sometimes radically. Clays can provide information about source terrane and climate, depositional environments and diagenetic history: in short, most of the questions geologists ask about rocks. They also impact petrophysical and engineering parameters. Clays can be extremely informative if you can get past the fear and ask the right questions; but it's not necessary to know minutiae.

Clays occur in complex mixtures of detrital and diagenetic clays. Keep in mind that only one or two clays may be in equilibrium at current conditions; any other clays must be unstable minerals. Figuring out which are which is part of the problem.

Clays are important, not only to shales and mudstones, but also to carbonates and coarser siliciclastics. Clays are significant, if not critical, components in almost all sediments, except the cleanest carbonates, coarse siliciclastics, or chemical sediments, and may be important even in those through diagenesis (**Figure 1**). Weaver (1958) thought that clays occur in more than 95 percent of all sediments. Because of their ductility and sheetlike geometry, clays often control pressure solution; because of their high surface/edge areas and ionic activity, they control the geochemistry; and because they often control porosity, they impact the mobility of fluids and ions in the rock.

However, clays are particularly useful for understanding unconventional resource plays, especially Paleozoic and Paleozoic-like organic-rich mudstones (Schutter, 2016). Even if they are only a small fraction of the minerals present, clays dominate the chemical and physical processes involving the rock. Because of their high surface (and edge) to volume ratios, as well as their ability to exchange ions and adsorbed molecules (Kennedy et al., 2002), they participate in many reactions within the rock. Because they are ductile and sheetlike, they may profoundly affect the mechanical properties of the rock, particularly if they are aligned in a preferred direction. Their impact is often magnified by weathering; clay content that is not obvious in the subsurface is amplified in the outcrop (and often by exposure to drilling fluids). They can change in regular, understandable ways, which helps with understanding depositional environment and burial history.

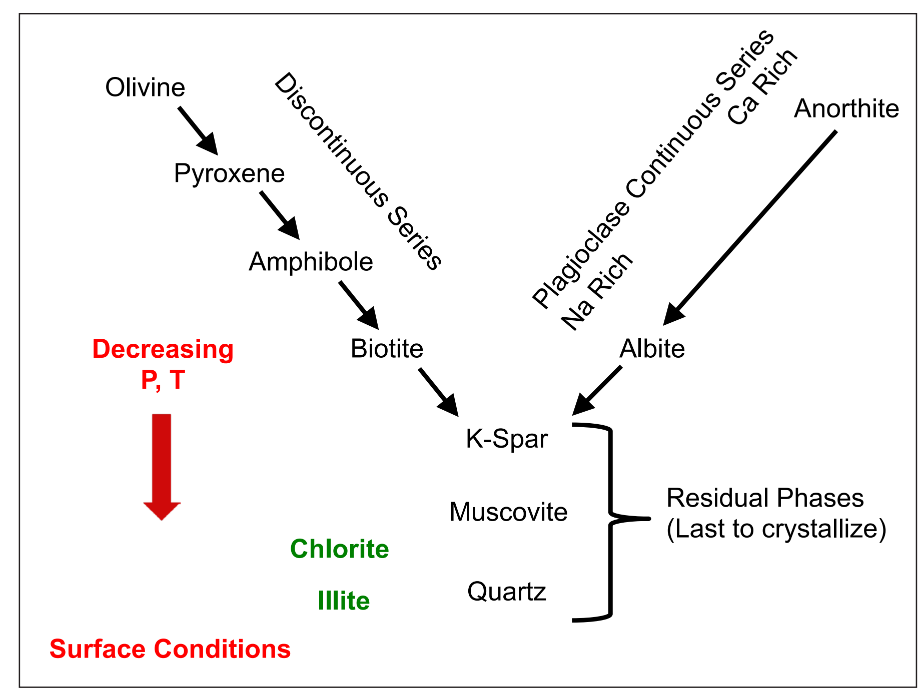


Figure 2. *Goldich's weathering series. This is derived from Bowen's reaction series for igneous minerals. Goldich concluded that those minerals which were most stable near earth-surface temperature and pressure conditions would weather more slowly than those which were stable at higher temperature and pressure conditions. Illite and chlorite are stable at close to earth-surface conditions.*

There should be a testable model or assessment of which clays should be present, how they are distributed and what properties and characteristics might be expected. This is compared to observations, with the differences driving the analysis. Clays can be predictable, and potentially amenable to modeling. Understanding their deposition and diagenesis can lead to exploration models for both conventional and unconventional hydrocarbon resources.

If you pay attention to a few basic rules, you can answer many questions about your rocks; you can avoid problems and find patterns.

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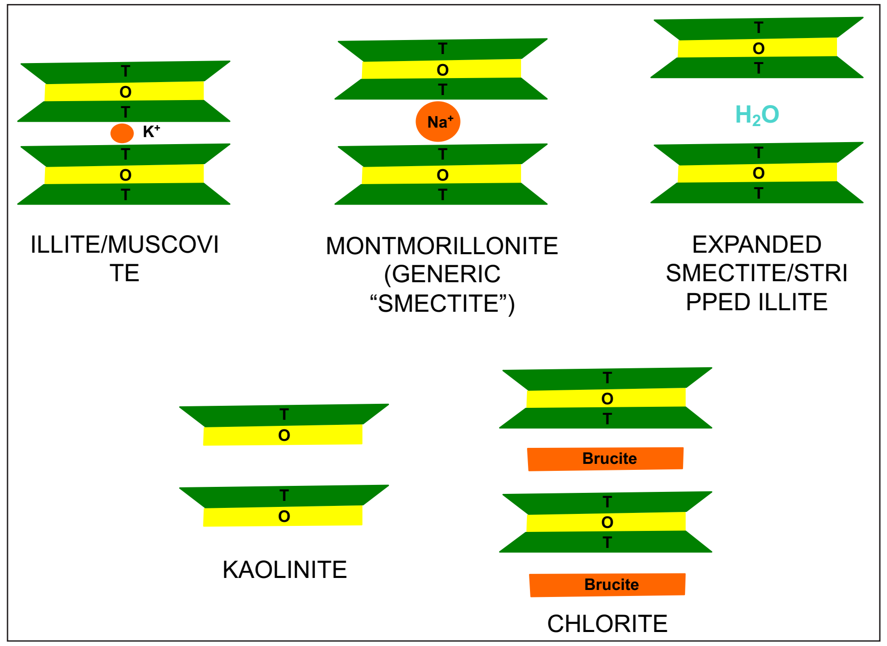

Figure 3. *Schematic diagram of clay structures. T=tetrahedral layer (usually Si and Al); O=octahedral layer (usually Al, Mg and/or Fe). The important elements of the clay mineral structure are the cations in the tetrahedral layers (with each cation coordinated with four oxygen ions), the cations in the octahedral layers (with each cation coordinated with eight anions, but not every cation space occupied) and the interlayer cations, often exchangeable. Most clays have two tetrahedral layers for every octahedral layer; kaolinite had only one of each. Chlorite has a brucite sheet instead of the single interlayer cations. Note that the "expanded smectite/stripped illite" is essentially the same for illite minus the interlayer K+ and montmorillonite minus the interlayer Na+.*

CLAY MINERAL	INTERLAYER	OCTAHEDRAL	TETRAHEDRAL
Muscovite	K	Al_2	$AlSi_3$ (2)
Illite	K, H_2O	$(Al, Mg, Fe)_2$	$(Si, Al)_4$ (2)
Glauconite	K, Na	$(Fe^{+2}, Al, Mg)_2$	$(Si, Al)_4$ (2)
Smectite			
Montmorillonite	$(Na, Ca)_{0.33}$	$(Al, Mg)_2$	Si_4 (2)
Beidellite	$Na_{0.5}$	Al_2	$Si_{3.5}Al_{0.5}$ (2)
Nontronite	$(Ca_{0.5}Na)_{0.3}$	Fe^{+3}_2	$(Si, Al)_4$ (2)
Kaolinite	–	Al_2	Si_2 (1)
Chlorite	$(Mg,Fe)_3(OH)_2$ brucite	$(Mg, Fe)_3$	$(Si, Al)_4$ (2)

Figure 4. *Comparison of principal clay minerals (cations). Oxygen and attached water are left out for simplicity. (Clay formulas from Wikipedia)*

Rule 1. There is a Basic Clay Suite

While there is no generic "clay," there is a basic clay suite. Just as quartz sand is the basic sandstone mineralogy, and departure from that indicates variation in the story requiring investigation, so too with the basic clay suite. Broadly, it consists of illite, weathered illite, and subordinate chlorite.

Illite is the basic stable clay under most surface conditions. Weaver (1959) stated that it was the most abundant clay in shales; he also noted (1958, 1960) that it dominated marine black shales. It is essentially muscovite with some of the ionic sites substituted or unfilled. Because of this close relationship, illite and muscovite are sometimes classed together in analyses as "micas".

Consider the Goldich weathering series (Goldich, 1938) (derived from Bowen's reaction series) (**Figure 2**). The lowest minerals in the series are those closest to stability at the earth's surface, including muscovite. The lowest temperature/pressure metamorphic facies (gradational into diagenesis) is the zeolite facies, characterized by muscovite and chlorite (Smulikowski et al., 2007). This not only indicates the clays that are most stable at earth surface and near-surface conditions, but also those that are most likely to be reworked from low-grade metasediments containing those minerals.

Basic clay structure consists of a series of sheets, with similar structures and an infinity of geochemistry (**Figure 3**). The basic building blocks are tetrahedral sheets and octahedral sheets. Tetrahedral sheets consist of cations (usually Si or Al) that share four oxygen anions. The tetrahedral, with shared oxygen at their vertices, expand in two directions, resulting in a sheet. Because of the way the tetrahedral connect, they actually have a honeycomb pattern, with a series of interlocked rings (with a silicon tetrahedron at each vertex) and spaces between. The tetrahedral sheets alternate with octahedral sheets. There, the cations are in octahedral coordination with oxygen; they usually consist of Mg, Al, and sometimes Fe. Oxygen anions can be shared between the tetrahedral and the octahedral layers, binding them tightly together.

The third component of clay structure is the interlayer site. Sometimes it contains just weakly attached H_2O, held by hydrogen bonds. Often, it is a cation, held more closely by covalent or ionic bonds. The strength of the bonds often depends on how tightly they fit into the holes in the sheet structure. But there are other variations. In the chlorite structure, a complete layer may be present. Ideally, it may be structurally a brucite, which is similar to an Mg octahedral layer, but the cations may or may not share oxygen anions with adjacent tetrahedral layers. Also, the interlayer spaces can hold all sorts of other molecules, particularly organic molecules of all types.

The different clays are distinguished by how the tetrahedral, octahedral, and interlayer components are arranged (**Figures 3, 4**). These typically fall into specific ranges, and are defined on that basis. The variations impact the physical properties of the various clays, and are related to the environments that produced them.

Looking at it from another direction, clay structure is dependent on the size of the ions involved as much as it is on their ionic charge (charge deficits can always be accounted for with the adsorbed ions or compounds). The clay sheets are held together by interlayer ions or hydrogen bonds; the stability of the clay is dependent on how well those interlayer ions can be moved. The K^+ ion fits into the holes in the sheets very well, making illite a more stable clay. Thus, just as quartz is the lowest entropy state for coarser siliciclastic minerals, illite is for clays.

The alteration of expandable clays (smectites) to illite with burial is widely known; Rask and others (1997) summarized it as requiring the input of K^+ and Al, and resulting in the release of Si and Fe. But there may be similar diagenetic reactions relating to other clays. Rask and others (op. cit.) suggested that illitization may also result in some chlorite formation, as a sink for the Fe in the smectites. Kisch (1983) and Środoń (1979) suggested that kaolinite may also alter to illite with burial.

The stability story is very similar for chlorite, but it comes from an environment richer in Fe^{+2} and Mg^{+2}, as well as having a different basic structure than illite. Like illite/muscovite, chlorite is stable at the lowest levels of metamorphism, as well as at surface conditions. Weaver and Pollard (1975) stated that chlorite occurs in 75 to 90 percent of all sediments, with the bulk of it being detrital. Chlorite may form diagenetically from smectite and kaolinite when a source for Fe and Mg is present (Bjørlykke, 1998). However, Liebling and Scherp (1980) noted that Fe, Mg-rich chlorite weathers more quickly than illite.

Thus, the basic clay suite expected in an ordinary clay shale (or other rocks containing detrital clays) is illite (and weathered illite) with subordinate chlorite. Variations require explanations.

Rule 2. Clays Are not Stoichiometric

Clays are usually described with fearsome chemical formulae, usually describing a unit cell. The implication is that clays can be adequately described by a specific composition. However, this is often not the case, particularly for detrital clays. Solid solution substitutions are the norm for virtually every cationic position; lattice vacancies are also normal. Anions may also be substituted, and attached water is abundant. Fortunately, this complexity involves understandable basic structures (**Figures 3, 4**). However, clays still have infinite variability; this is expressed in the characteristic charges (from unbalanced electrical issues) which is why clays flocculate. In clays, the size of the ion is often more important than its charge; it needs to fit in a space in the lattice. Imperfect charges can be compensated for elsewhere (thus, the ubiquitous solid solutions).

Weaver (1958) observed that the basic clay lattice was inherited from the source material, and is the most significant parameter; the basic lattice is modified by secondary adsorbed cations, reflecting the depositional environment. This basic principle is often obscured by nomenclature; understanding how clays work is more important that what they are called (which may give rise to false relationships).

Detrital clays not only have infinite chemical variation, but since they are weathered and transported, they are infinitely reshuffled. Clays in any sediment contain a vast range of compositions.

These detrital clays cannot be adequately described by comparison to a standard, because no standard is adequate. For example, with X-ray diffraction (XRD), the intensity of the peaks is a function of just which ions in the solid-solution series occupies the sites, and what their precise spacing is. There is some validity to comparing adjacent or similar samples using the same methodology, since trends can be described, but comparing unlike samples, particularly from different labs (and lab procedures) is best described as "semiquantitative." (The numbers may be precise, but what they are describing is imprecisely quantified.) Moll (2001) added that clay mineral suites can change significantly in a few cm; he proposed that a standard should be produced by homogenizing a single large volume, with all future studies based on that sample. It is an arbitrary solution, avoiding the issue of clay variability, how to describe it, and what it means.

X-ray fluorescence (XRF) suffers from a related problem. Since the fluorescence can be assigned to the amount of a specific element

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present, it would appear to be more reliable. But since clays do not have constant elemental ratios, the total amount of an element present can be ambiguous. For example, weathered illite has extremely variable potassium content. An XRF value for potassium could have no relationship to the amount of illite present. XRF results are also "semiquantitative" – they assume a stoichiometric formula, and can be compared on that basis, but it is necessary to remember that there may be a very large error bar. Add in the possibility of detrital or authigenic K-feldspar, and/or other potassium-bearing minerals, and the problems may be unmanageable.

Note that these comments do not apply to authigenic or diagenetic clays, which may form over a very narrow range of conditions, and consequently may be stoichiometric. When they occur by themselves, or in an identifiable fraction, they may be adequately quantified.

One of the principal objectives of XRD and XRF is to determine where the cations are housed, as this goes a long way toward understanding the physical and chemical properties of the minerals involved, how reactive they might be, and the history of the rock involved. Relying on XRD or XRF alone is much like evaluating a polynomial value with too many variables. Using XRD and XRF together can be like solving two parallel equations; it permits a much better solution to the variables.

The assumption of stoichiometry of clays can have vast implications for petrophysical interpretations. The amount of clay present (Vclay) was found to be poorly related to a simple gamma-ray log (Hurst, 1987). The amount of potassium present (from a spectral gamma-ray log) may still be suspect, since it assumes one uniform clay with a constant potassium content; to the extent that this is not true renders the calculations suspect. Logs based on water associated with the clays (such as microresisitvity or neutron porosity logs) may give different answers, but may also depend on assuming a uniform clay suite. The practice of finding two end members (shaly and non-shaly) and interpolating between them, assuming a uniform clays, is inherently suspect. However, better understanding of clays and how they vary holds out the possibility of improved petrophysical analysis.

Rule 3. Kaolinite Requires an Explanation

As noted above, the basic clay shale is expected to contain illite (including weathered illite) and subordinate chlorite. Other clays may be present, and may be expected, but because special conditions must be involved, then an explanation is called for.

The best example is kaolinite. Kaolinite is a common clay, but not so abundant or stable that it is ubiquitous. In contrast to illite and chlorite, which broadly express slightly basic conditions with significant cation activity (particularly $^{K+}$ for illite), kaolinite forms in acidic conditions, with hydrogen activity greater than that of other cations. That means at surface conditions it is generally terrestrial, often associated with vegetation and lateritic weathering. Weaver (1958, 1960) stated that continental black shales tend to be kaolinite-bearing, while marine black shales are illitic. Keller (1970) observed that kaolinite, often accompanied by gibbsite, may be an indicator of low-latitude provenance, but that it apparently disappears in a marine environment. Grim (1968) stated that kaolinitic shales reflect a kaolinitic source.

Another important source of kaolinite is diagenesis. Kaolinite seems to be particularly abundant in carbonates, where it frequently fills pores. It also occurs in supermature orthoquartzites, which apparently lack even detrital feldspars or rock fragments. While the high ratio of hydrogen ions to other cations may be important, the lack of other cations (K^+, Mg^{+2}, Na^+, Ca^{+2}, Fe^{+2}) may also be critical; a high Al:Si ratio may also be important (Keller, op. cit.). Bjørlykke (1998) suggested that a through flow of meteoric water may be necessary to reduce the cation and silica concentration enough to form kaolinite. Berger and others (1999) briefly discussed the possibility that kaolinite may diagenetically convert to mixed-layer illite/smectite, but concluded that alteration to chlorite was more likely. On the other hand, Środoń (1979) and Kisch (1983) favored the alteration of kaolinite to illite with burial. The diagenetic range of kaolinite is apparently limited as well.

The issue of kaolinite comes up with the Eagle Ford Shale (discussed below). Some workers (Fein, 1994; Macquaker et al., 2014; McAllister et al., 2015) suggest that the formation of carboxylic acid from the organics favors formation of kaolinite, while Maliva and others (1999) suggest decarboxylation in organic-rich pore waters would promote release of Al+3 from organo-complexes and thus favor kaolinite precipitation. Both models suggest organic-rich mudstones should be kaolinitic; Weaver (1958, 1960) observed that this is the exception, as most are illitic. Neither organic-dependent model would explain the kaolinite in supermature orthoquartzites. Most of the models have been applied to organic-rich clay mudstones; it is not clear how well they would apply to kaolinite distribution in clay-poor, sometimes organic-poor, carbonates and mature siliciclastics.

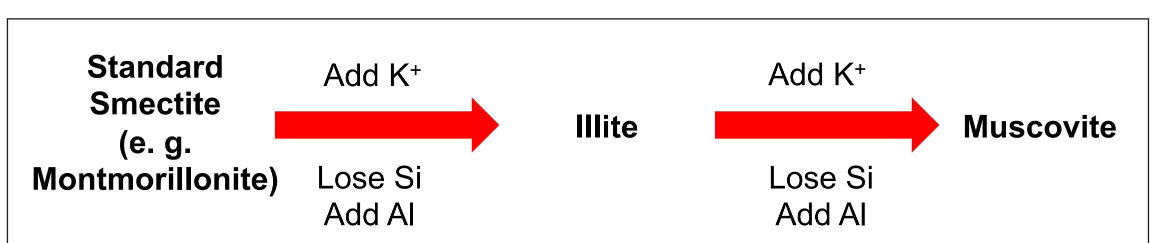

Figure 5. *The illitization process (from burial diagenesis) begins with smectite. K^+ and Al are added, and Si lost, to make illite. If the process continues to completion, the illite becomes muscovite.*

Kaolinite is sufficiently uncommon (in terms of total volume) that it is not generally expected to be significantly present due to reworking of older-cycle kaolinitic rocks. Grim (1968) stated that kaolinitic shales reflected a kaolinitic source. When kaolinite is not from a contemporaneous weathering environment, it can be linked to specific kaoliniitc source, providing specific information on uplift and erosion patterns. Kaolinite needs an explanation.

Rule 4. There are Different "Smectites"

"Smectite" is essentially a catch-all term, referring to three-layer (TOT) clays which have the capacity to expand when water or a substance like ethylene glycol is added. This means that there may be true "smectites" (with a specific structure) and clays that act like "smectites," with unfortunate results in interpretation and diagenetic modeling. (This becomes even more confusing in older literature, where "montmorillonite" – which correctly refers to a specific expandable clay species – is used interchangeably with "smectite.") The "smectites" present must be understood to properly understand the rock.

It has not been widely recognized that when the K+ ion is stripped out of illite, the resulting stripped illite is expandable. This can happen at surface conditions, particularly in paleosols with active K^+ uptake by plants. Keller (1970) referred to such illite as "stripped," "open," or "degraded." These clays are sometimes also described as "vermiculite." Rich (1964) and Stepusin (1978) noted that the expanded layers could be propped open by Al^{+3} and other hydrated ions, and so would not collapse completely when heated (making identification more problematic).

In contrast, the more standard or true "smectites" are those like montmorillonite, that form from volcanic ash, or the weathering of crystalline igneous or high-grade metamorphic rocks, where the high activities of many cations, particularly Na^+ and Mg^{+2}, along with high silica activity, result in favorable conditions.

This becomes a critical difference when discussing diagenesis and "illitization." Most true "smectites" have more silica in the tetrahedral layers of the clay sheets (**Figures 3, 4**); the standard model of illitization calls for some of the silicon to be replaced by aluminum, releasing silicon into the environment (Eslinger and Pevear, 1985) (**Figure 5**). The heat of burial is necessary to provide the energy needed. Eberl and Hower (1976) noted that this would happen so slowly at ocean-bottom conditions as to be insignificant. Środoń and Eberl (1984) stated there is little evidence that montmorillonite or kaolinite convert to illite in the oceans; Eslinger and Pevear (op. cit.) observed that analysis of the kinetics indicated it would take 600 Myr to convert montmorillonite to illite in a marine environment.

In contrast, stripped or weathered illites have not gained silicon or lost aluminum during weathering; restoration of the K^+ returns them to the standard illite state. This apparently requires no more than spending a period of time in seawater; Weaver (1967) and Keller (1970) noted that "stripped" illites rapidly absorbed K^+ in seawater; Powers (1957) observed that weathered illite became more crystalline as it passed down an estuary. This relates directly to Weaver's (1958) observation that the clay lattice is inherited, while the exchangeable cations reflect the depositional environment. Such stripped-illite "smectites" would not yield free silicon during burial diagenesis; also, since they close to their illite structure in seawater, they would not have available sites for organic molecules or extra water, restricting their reactions during hydrocarbon generation.

(Notably, this process is supported by the pattern in glaucony, an Fe-rich illite, where Amorosi, 2012, noted that "mature" glaucony contained more K and has a higher crystallinity.)

One of the implications is that the collapse of "expandable" clays and the interchange of Si and Al in the tetrahedral layer are two separate processes, and may take place under different conditions. In the past, these have been rolled together as "illitization," implying one set of conditions for a single process.

So why hasn't this been recognized before? How important is it? First, recognition depends on finding the right setting, with only stripped illite present; then, it depends on sampling it in such a way to recognize the patterns and what they mean. Berger and others (1999), reviewing developments in illitization, noted that several different structures of mixed-layer clays were involved; they were often found together in the same sample in a diagenetic sequence. Rask and others (1997) also recognized a two-step model for illitization, with the presence or generation of a high-charge, Al-enriched clay at shallower depths (which presumably includes stripped illite), followed by later fixation of K and dehydration with continued burial.

Most of the diagenetic models, particularly those for "illitization," are based on sediments from the Gulf of Mexico basin (e. g., Burst,

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1969; Perry and Hower, 1970; Hower et al., 1976; Berger et al., op. cit.). The Cenozoic sediments, and probably the Late Cretaceous sediments as well, have abundant true smectites from the volcanics and primary crystalline rocks of western North America (Potter et al., 2005, p. 161-162); the Cenozoic glacigene sediments may also be rich in true smectites, since they contain finely-ground (and reactive) minerals from the crystalline basement.

Lahann (2017) observed the same phenomenon in the Gulf of Mexico, concluding that the wells in the Pliocene section of the offshore eastern Mississippi Delta region had far less smectite than those off Texas. Until the Plio-Pleistocene rerouting of the upper Missouri and Ohio rivers, the paleo-Mississippi had a relatively small input of sediments from the west; the paleo-Tombigbee/Tennessee (a more important system in the Miocene) derived sediments exclusively from the Appalachians, which are illitic, possibly with stripped illite and kaolinite. This pattern applies not only to the clays, but was confirmed by detrital zircon evidence (Xu et al., 2017).

North American Paleozoic sediments, in contrast, would be expected to be poor in true smectites, and with most expandable clays present being stripped illites. [For example, Guthrie and others (1981) noted that the Mississippian and lower Pennsylvanian shales in Oklahoma and Arkansas were illitic and chloritic, with minor mixed-layer clays.] During most of the Paleozoic, tropical weathering, mostly of older sediments, was the rule. Stripped illite would be the first step. Illitization of the type modeled in the younger Gulf of Mexico sediments, would be unlikely to take place since the stripped illite had reverted to illite upon being deposited in a marine environment. This is consistent with the observation of Eslinger and Pevear (1985) that smectite, mixed-layer clays and kaolinite were rare in the Paleozoic [they suggested diagenesis was the reason, but provenance and environment seem more likely; again, this pattern is consistent with Lahann's (op. cit.) observations].

An example can be found in the Upper Pennsylvanian sediments of the Midcontinent (Schutter, 1983). There, detrital muscovite and kaolinite mark sediment influx from outside the basin; in some cyclothems in the Forest City Basin, it can be shown that outside sediments are absent, and any clays present are derived from the weathering of local limestones. The paleosols show evidence of progressive weathering (see **Rule 11**), but the marine beds show increasing illite crystallinity, apparently inversely proportional to the rate of sedimentation (corroborated by other lines of evidence) (**Figures 6, 7** and **8**). This changing illite crystallinity must be due to depositional processes; there is no evidence of clastic influx, and burial diagenesis would be expected to homogenize the signal. Algeo and others (2004) found a strongly similar pattern in the immediately underlying cyclothem in the Forest City Basin. The black shale had an anomalously illitic zone, with the Al_2O_3/SiO_2 ratio indicating nearly pure highly crystalline illite. Other lines of evidence, such as the high concentration of trace metals and the preservation of only the most resistant organic material, indicated very low rates of sedimentations (Schutter, 2016). Chamley (1989) cited evidence that strongly-reducing environments favor high illite crystallinity by destroying smaller, poorly crystallized mixed-layer clays; that does not apply here, as the highly crystalline marine illite persists beyond black shale deposition.

An obvious question is how to tell if abundant weathered illite is important to the interpretation of a clay suite. The best indicator is probably to examine the least diagenetically altered section on the margin of the basin and find the changes in illite crystallinity between the most marine and the least marine sediments. While not definitive, that could

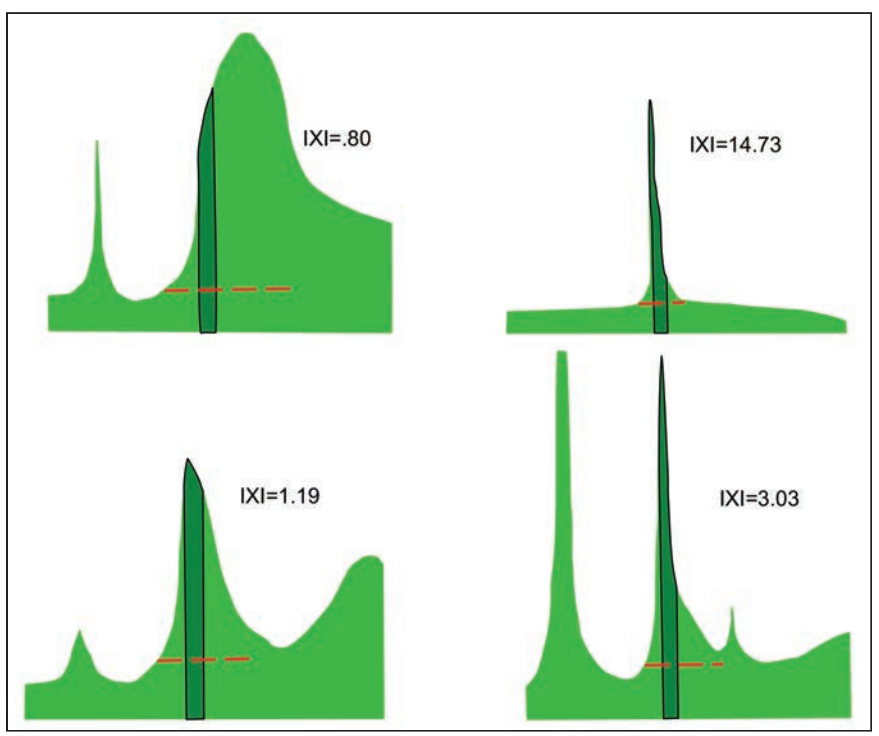

Figure 6. *Illite crystallinity index, comparing the values from XRD at about 10Å and 10.5Å, after the background has been subtracted (dashed red line). An IXI of .80 shows significant mixed layers, while an IXI of 14.73 is essentially pure crystalline illite. This method is in contrast to standard illite crystallinity calculations, which are based on the width of the illite peak at half-height. In weathered illites with abundant random mixed-layer clays, the width at half-height may become null. IXI=illite crystallinity index. (For details, see Schutter, 1983.)*

indicate how much the "smectite" responds to surface conditions. Additionally, it would identify a baseline clay suite for diagenetic analysis.

An implication is that the presence of true smectite (particularly in significant volumes) in a sediment cannot be assumed. Conventional illitization would be expected only when true smectite is present. (Beyond that, it is also worth noting that beidellite, a true smectite, is also silica-poor, and unlikely to yield significant Si during illitization.)

The issue of two smectites has other implications. The observations of Kennedy and others (2002) regarding the relationship of clay surface areas and organic adsorption (which they suggest is key to source rock quality) is strongly linked to this. They note that smectite has a particularly high surface area, and thus has a much higher potential for organic adsorption. It is not clear if this means only true smectites or includes stripped illites. With stripped illites, there would be also be the issue of K^+ uptake in a marine environment; would K^+ force out adsorbed organics, or would adsorbed organics inhibit K^+ uptake? Johns and Shinoyama (1972) noted that smectites catalyze the transformation of organic matter into alkanes and cracking them into shorter chains; this might also depend on which smectite was present. Bruce (1984) noted that burial illitization included dehydration of the smectite, and suggested the free water thus available might provide a vehicle for hydrocarbon migration. If the available stripped illite recrystallized in a marine environment, this mechanism would not be available (and might also enhance retention of organics by the source shale). This dehydration may also be connected to overpressuring of (true) smectite-rich mudstones; Lahann (2017) noted that smectite-poor mudstones in the Pliocene of the offshore eastern Mississippi Delta had overpressures attributable to simple compaction, while the smectite-rich mudstones off Texas had additional overpressure attributed to illitization.

The possibility that stripped illites may readily lose K^+ in weathering profiles and regain it in seawater indicate that conclusions drawn from K/Ar dating of illites are suspect, since the clays are open systems in respect to K^+; the retention of Ar would presumably be even worse. [Eberl and others

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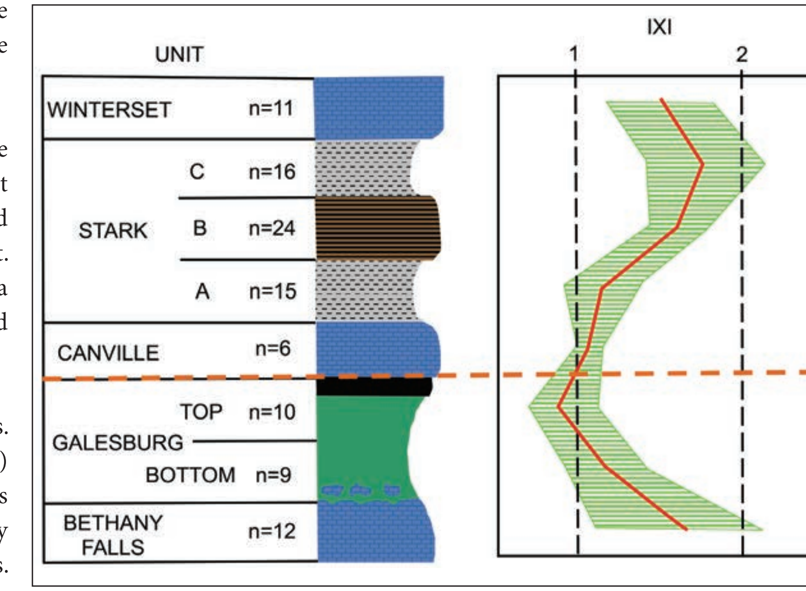

Figure 7. *Illite crystallinity values through an Upper Pennsylvanian cyclothem from the Forest City Basin. Illite crystallinity varies systematically. Note that the highest crystallinity is in the most offshore facies with the lowest rate of deposition, and the lowest crystallinity is at the top of the soil profile (the dashed orange line marks the initial flooding surface). There is no kaolinite or detrital muscovite present. The curve should not exist at all if diagenesis controlled the crystallinity pattern. The solid red line is the mean value; the shaded green zone is one standard deviation from the mean. The number of samples from each horizon is shown; these come from multiple outcrops and cores across the basin. The section averages 3 to 4 m thick. (IXI=illite crystallinity index; see Figure 6)*

Figure 8. *Outcrop example of the cyclothem discussed in Figure 7. (Galesburg Shale and Dennis Formation near Davis City, southcentral Iowa.) Note the yardstick (approximately 1 m) at center. The Stark black shale is above the deep shadow; the Davis City Coal is the black streak behind the yardstick. The basal Winterset Limestone is just above the Stark; the top of the Bethany Falls Limestone is just above the water line in the lower right. Note that the Galesburg paleosols is less than 2 m thick; it contains no kaolinite, detrital muscovite or quartz. The clay mineralogy is compatible with weathering from the corroded Bethany Falls. Both the Stark black shale and the Galesburg paleosols are noncalcareous.*

(1990) also noted that the diagenetic growth of illite crystallites could result in younger overgrowths on older cores, resulting in the apparent paradox of decreasing radiometric age with depth. The conclusion is that radiometric dating of illite should be treagted with caution, but if it is understood, it can yield some valuable information.]

Hancock (1993) noted that smectitic clays have a different Th:K ratio than illitic clays; it is not clear if the "smectitic" clays include stripped illite, but that would be reasonable, as the loss of K^+ would impact the Th:K ratio. If that is true, then the Th:K ratio may provide another way to analyze the clays and their depositional history. K^+ uptake by weathered illite would presumably differ from Th uptake (if that took place at all). The changing Th:K ratio through a section could provide valuable evidence of the processes (and their rates) involved.

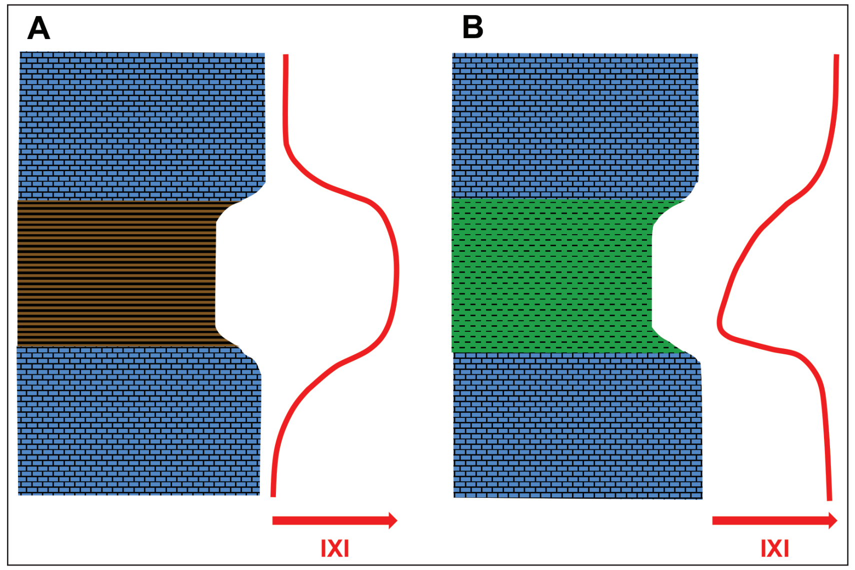

Figure 9. *Contrasting clay mineral patterns of condensed shales and distal clastic shales. In A, failure of the masking deposition is marked by the same clay suite, but the illite crystallinity is higher in the shale, indicating slower deposition. In contrast, B illustrates a distal siliciclastic influx. The clay suite in the shale may be the same as or different from the adjacent units, but it has more weathered and less crystalline illite, which had less time to reabsorb K+. (IXI=illite crystallinity index; see Fig. 6)*

Note that sedimentary illitization (the uptake of K^+ by stripped illite) is not an argument that diagenetic illitization does not take place; it clearly does, but begins at about the onset of hydrocarbon generation (Lahann, 2017). Diagenetic illitization would be expected to overprint and homogenize illitization patterns from sedimentary environments. The depositional environment signal would be dominant in submature sediments; the issue is being able to discriminate as the sediments become more mature with burial.

Rule 5. Clays May Indicate Relative Rates of Deposition

Organic-rich mudstones are often assumed to be a distal part of a siliciclastics influx, and/or rapidly deposited. Both assumptions may be invalid. Organic-rich mudstones may be a result of the failure of masking sedimentation (especially carbonate) which dilute and obscure them, which is why the organic-rich mudstones are often associated with condensed sections. The rate of sedimentation is not necessarily high; it may be relatively high only during brief episodes, as required to bury unstable organic material. Study of the clays in the mudstones, compared with the clays in the adjacent units, may help clarify this situation (**Figure 9**).

Illite crystallinity may be particularly useful, as it apparently varies with the length of time the stripped illite interacts with sea water. If an organic-rich mudstone has the same detrital clay suite as the adjacent units (generally carbonates), but higher illite crystallinity, the implication is that sedimentation was slower, likely due to the failure of masking (carbonate) sedimentation. If the shale is related to a siliciclastic influx (such as a prograding delta), the clays would be more weathered, with a lower illite crystallinity. Possibly, the clay suite would differ from the ambient clay suite, and the mudstone might include diagnostic detrital grains, especially micas.

Note that this principle is illustrated by the clays in **Figure 7**. The clay suite, similar throughout, contains the illite with the highest crystallinity in the offshore condensed section, with the slowest deposition. There is no evidence of a clastic influx or rapid deposition as the source of the black shale. As noted in the previous section, the highly crystalline illite occurs in the offshore marine facies above the black shale, so it is not a function of the reducing environment.

Since the rate of deposition may be expressed in illite crystallinity, it is possible that there is a correlation between the porosity of a shale and illite crystallinity. Increasing illite crystallinity may be inversely proportional to porosity. While far from being the only variable, the possibility of a correlation suggests illite crystallinity may be used as a predictive tool. (Note that this parallels the discussion of the Th:K ratio in the previous section.)

Rule 6. Clays Can Be Detrital and/or Diagenetic

The clays in any given rock can be detrital or diagenetic in origin, frequently both. A simple clay analysis cannot identify whether the clays reflect depositional conditions or diagenesis, or both. Understanding this can have profound influence on interpreting the evolution of the geochemical system and the basin history. Unfortunately, bulk XRD or XRF doesn't help. They may identify

the total clay suite present, but not whether the clays are all stable in relationship to each other or the rest of the rock.

Heroux and others (1979) noted that the coarser clay fraction is less likely to be altered. Diagenetic clays may be overgrowths on detrital cores, or may be neoformed. Consequently, they may be similar to the detrital clays, or represent a new chemical equilibrium. For example, detrital illite is dominantly the $2M_1$ polytype, while 1M and 1Md polytypes are diagenetic (Weaver, 1958; Grathoff et al., 2001). (The 2M1 polytype has a higher degree of symmetry.) As the illite grain size decreases, $2M_1$ decreases in relation to the proportion of 1M and 1Md, and the ages of the smaller fractions progressively decrease.

Petrophysical analyses may be based on assumptions about whether the clays are diagenetic or detrital. Beyond the assumption of a simple illite chemistry, Hancock (1993) noted that smectites and kaolinite may contain higher levels of Th. This is true for detrital clays derived from terrestrial weathering, but may not be supportable for diagenetic clays, especially those forming from dilute solutions. Closer consideration may provide valuable evidence of the systems involved.

Identification of all the clays present, understanding their physical properties, chemistry, and relationships can be crucial in designing well completion programs, since some of the clays may be sensitive or prone to migration; chemical instability may also result in unfortunate reactions.

Probably the best way to deal with the problem is scanning electron microscopy (SEM) and related techniques. Diagenetic clays are usually readily identifiable, with well-developed crystals; detrital clays are generally ragged and abraded, and are often difficult to image. (SEM photomicrographs are biased toward the photogenic.)

Although not an accurate measurement, a first pass evaluation might be to X-ray different size fractions of clay. Generally, authigenic overgrowths are smaller than the detrital cores (as well as being somewhat different in structure, since they may have different stacking patterns). In structure, a clay sample from the <1µm fraction might have a greater percentage of diagenetic clays than a sample from the <10µm fraction. Comparison of the clay mineralogy of the two size fractions may indicate if there is a problem, and what the nature of the problem might be.

Peak sharpness may help, too, particularly of the 001 peak (diffracted by the layers parallel to the sheety cleavage). Diagenetic clays have very sharp, narrow peaks; detrital clays (especially illite) are weathered, and have broad, lower peaks because of the variable chemistry. A combination (weathered detrital cores with diagenetic overgrowths) is also possible.

Rule 7. Size Matters

From the foregoing discussion on detrital versus diagenetic clays, it is clear that different size fractions of clays can have different mineralogies. This applies to detrital clays alone, as well. Some clays have different size ranges. For example, kaolinite frequently occurs as large particles, perhaps because it often occurs as pore-filling large platelets. Illite, too, is frequently larger than average, although not as large as kaolinite. Gibbs (1977) observed that the various clays carried by the Amazon had different mean sizes; Baker (1973) found that only samples including larger grain sizes (up to 63µm) accurately represented transported grains. Eslinger and Pevear (1985) cited examples which found large deltas to be more kaolinitic close to the channel mouths, becoming more smectitic offshore, because the coarser kaolinite settled faster. Goudge and others (2017) and Wang and others (2017) provide recent examples where clay mineralogy varied by size distribution.

Thus, standard clay slide preparations, designed to analyze the <2µm clay population, may artificially skew the mineral distribution, leaving out the coarser clays; this, in turn, can impact the understanding of the bulk clay mineralogy, geochemistry, and the rock history.

With this in mind, it may be appropriate to process more than one sample; perhaps making sure one includes all the coarser clay particles (>2µm). This may give a better approximation of the bulk amount of clays present, and a better assessment of the impact of clays on the geochemical and physical properties of the rock.

Rule 8. There Are More Clays Than the Basic Clays

Most geologists, when they think about clays, think of the four common clays: smectite, illite, chlorite and kaolinite. They may add "mixed-layer" as a fifth, but since it is generally a mixture of smectite and illite, it's not really a distinct clay. Mixed-layer clays can also be divided into regularly interstratified and randomly mixed-layer (with the latter related to the stripping process). There may be some awareness that since clays are usually solid-solution series, the various end members may be recognized as distinct minerals, but this is rarely considered to be important.

Glauconite is a special iron-rich illite. [The term "glaucony" has been proposed for all green marine clays of indeterminate mineralogy by Odin and Matter (1981), but some workers restrict that term to the glauconite mineral.] Glauconite is diagenetic (and occasionally reworked), usually marking a horizon with low rates of deposition, sometimes with limited oxygen (at least interstitially within the sediment). Thus, it often marks a flooding surface, and is important to sequence stratigraphy (Amorosi, 2012). (This may apply more broadly to the other green marine clays as well.)

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Corrensite is another significant clay. It is a Mg-clay consisting of alternating Mg-smectite and Mg-chlorite layers (Poppe et al., 2001). It is commonly associated with evaporitic environments; it may be the clay analog of dolomite, formed when the Mg^{+2} activity goes up with the precipitation of calcite (April, 1981). Corrensite is a swelling clay that is not purely a smectite. It may occur in a shale where there are no other indicators of evaporites, and thus help with a broader environmental interpretation. (To be complete, corrensite can also form from the weathering of Mg-rich basalts and in Mg-rich hydrothermal environments, but that is not common.) Corrensite may begin as an Mg-smectite, or as the original depositional phase (Mg-smectites, like stevensite, are also associated with evaporitic environments, notably being reported from the Green River Basin and the pre-salt section of the South Atlantic Salt Basin). Corrensite may diagenetically collapse to chlorite (a parallel process to illitization) (Bristow et al., 2009; Rainoldi et al., 2015), and may be an explanation for shales with unusually high chlorite concentrations. Kopp and Fallis (1974) and April (op. cit.) suggested that corrensite is more widespread than recognized, but studies seldom look for it.

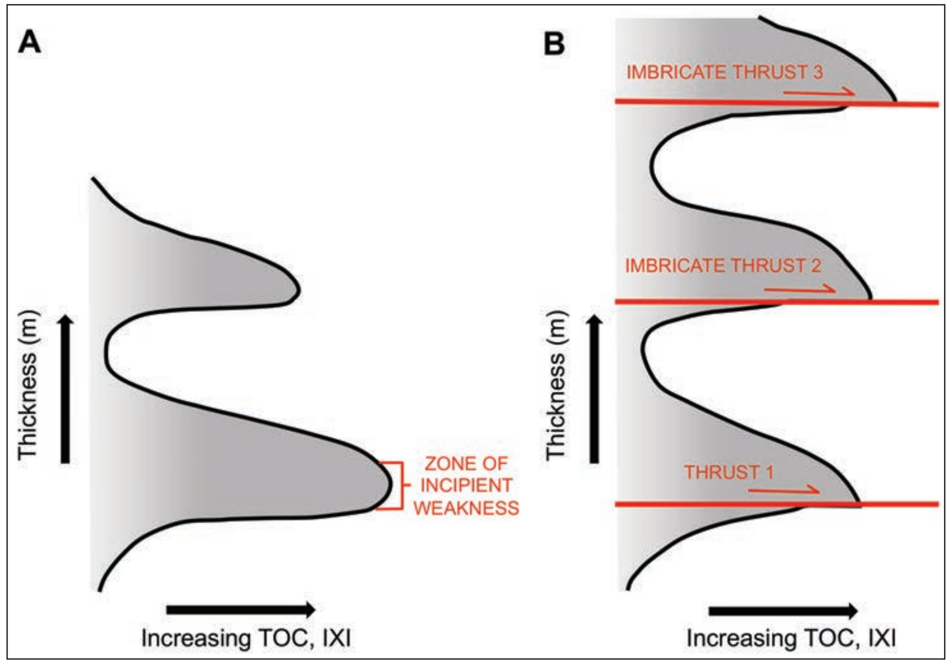

Figure 10. *Schematic diagram of thrust faulting in a black shale. A is pre-faulting, showing where the zone of highest TOC and highest illite crystallinity (IXI; see Fig. 6) would be the weakest horizon. This would be where thrusting would be expected (B); it could result in imbricate thrust sheets if the fault system propagated, or if there were more than one weak zone in the shale.*

In addition to the various end-members of the common solid-solution series of clays, in rare cases there are clays formed from the weathering of mineral deposits with unusual compositions. Thus we have clays like Zn- (sauconite) and Li- (hectorite) smectites and Ni- (nimite) and Mn- (pennantite) chlorites; these are rarely important in the hydrocarbon industry, but are occasionally ore and special purpose minerals.

Clays also come with a collection of polymorphs (different lattice structures for the same composition); beyond that, many clays have polytypes. Because some of the structural sheets (particularly the octahedral sheets) have empty spaces at regular intervals, the vacant spaces can change position in a regular way from one sheet to the next. The pattern of this change defines the polytype.

Both polymorphs and polytypes are generally indicative of specific pressure and temperature conditions, and if they can be determined by XRD and other techniques may provide more control points for basin modeling.

For example, dickite is a polytype of kaolinite. The critical temperature for the kaolinite-dickite boundary is within the oil window (Fialips et al., 2003), so the presence of dickite shows a level of maturity. This can be factored into the maturation modeling, as well as impacting the pore evolution. Ehrenberg and others (1993) discussed an example of a kaolinite-dickite transition (noting they could not be reliably distinguished by SEM). Similarly, $2M_1$ illite is a more ordered (higher temperature) polytype of illite (although not distinguished as a separate mineral).

Rule 9. Clay Suites Can Change Abruptly

It is probably not surprising that clay suites can change abruptly near faults, fractures, or porous units where altering fluids have access to the rocks and the clays in them.

But clay suites can also change abruptly across flooding surfaces. Clays imported by large rivers may be trapped elsewhere by rising sea level, with only local clays still present (e. g., Schutter, 1983, Figure 7). Such surfaces are also often marked with shelly pavements (indicating the advent of clear water and low rates of deposition) and an upward increase in organic matter. Eslinger and Pevear (1985) noted that the clay suites associated with the deltas of large rivers may be severely restricted by flooding of the shelves; wide areas of the continental shelf today are characterized by clays eroded and reworked from Pleistocene clays, and not prograding deltas.

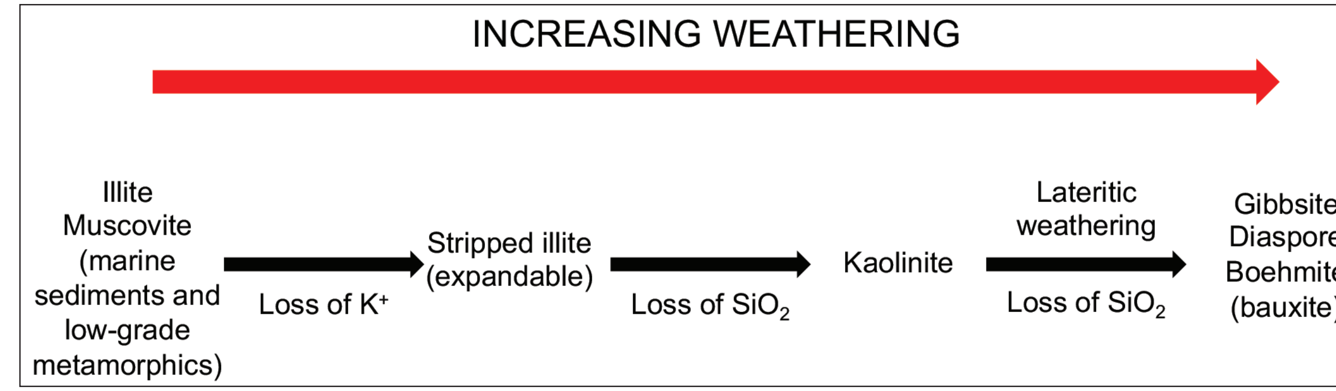

Figure 11. *Weathering of clays in paleosols. Weathering may begin with muscovite (low-grade metamorphics) or illite (marine sediments) as parents. Loss of K+ would result in stripped illite (which would be expandable), then kaolinte (with the loss of silica and other cations), and finally alumina/bauxite (gibbsite, diaspore, or boehmite). This is based on empirical observations; the precise chemical reactions have not been documented.*

Clay suites can also change not only with the on/off switch of changing sea level, but also with changing provenance. This can be quite pronounced, or more subtle. Eslinger and Pevear (op. cit.) cited evidence that the smectites in the northeastern Gulf of Mexico are more beidellitic (higher Al and less Mg, Ca) than that in the northwestern Gulf. They also cited the example of the Denver Basin, which had inputs of several identifiably different mixed-layer clays. Milliken and others (2017) in the course of their studies on the Recent sediments of the Texas shelf, noted that locally derived sediments were red and kaolinitic/illitic, while muds transported by currents from the Mississippi were gray and smectitic.

Likewise, clays can also mark unconformities, sometimes with important implications to hydrocarbon development. In one case, fine-grained marine Cretaceous sands, characterized by an illite-chlorite clay suite, were overlain by a coarse-grained fluvial Oligocene orthoquartzite with a kaolinite clay suite. Both were part of one reservoir, in communication with each other. Both units performed similarly on initial test, but actual production from the Cretaceous reservoir was seriously impaired. This suggests the possibility of fines migration blocking pore spaces, or the reservoir otherwise being sensitive to clay problems. In any case, the differing clay suites across the unconformity showed the need for different completion strategies, rather than a "one-size-fits-all" approach.

Note that the possibility that clay suites can change abruptly is a big problem for petrophysical analysis, which generally assumes clays have uniform properties throughout the section. Thus, an awareness of how and why clays may change is very important to petrophysics.

The possible abrupt changes in clay suites can also have implications in well engineering. Different clays suites can have different diagenetic pathways, giving rise to different rock properties. These can change over very narrow intervals. Some idea of the potential variability can be critical to avoiding problems.

Rule 10. Clays May Be Related to Structure

Although it may not be immediately evident, clays may be related to structural development. This is not in the sense that the clays cause a structure to develop, but the clays may show why a structure developed where it did, which may in turn enhance exploration and modeling.

For example, illite crystallinity increases as the rate of deposition declines. Declining depositional rate may also correspond to increasing TOC content, as diluting sediment falls.

Organic-rich sediments are mechanically weaker than the adjacent sediments, often with a higher water content, and possible overpressure and they are prone to deformation. Among other things, they may be preferential zones for thrust faulting (**Figure 10**).

In Alabama, the Cambrian Conesauga Shale is piled up into "mushwads" (Thomas, 2001), where imbricate thrusting has taken place within the organic-rich intervals. These mushwads have proven to be productive for commercial hydrocarbons (Pashin et al., 2011), but development has been problematic; among other reasons, because the internal structure and stratigraphy cannot be determined.

A similar situation in Sweden suggests a possible answer. Along the front of the Caledonian thrust, the Cambrian Alum Shale contains the principal detachment surface. It has been observed that illite crystallinity increases upward toward the thrust surface (Rickard et al., 1979). In a conventional model, this would be interpreted as illitization due to overthrusting with a hot thrust sheet from a deeper environment. This is a reasonable model, but

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there is an alternate interpretation. The upward increase in illite crystallinity could be an expression of decreasing sedimentation and increasing organic content, culminating at the surface of maximum weakness. (Note that this suggests the possibility of Alum mushwads along the thrust front with thrusting focused in weak organic-rich horizons.)

By this model, the mushwads of Alabama (and by extension, elsewhere) are not hopelessly chaotic internally, but are actually a series of imbricate blocks, detached along one or more distinct surfaces. Pashin (2008) observed this to be the case, with stacks of shale panels that maintained regional dip. These blocks or panels may be identified through the illite crystallinity in cores; once identified, the surfaces can be tied back to well logs and seismic data. Assuming the detachment surfaces are regionally consistent, they wouldn't have to be determined in every well, but extrapolated with a regional model.

Bruce (1984) suggested that burial illitization and the related dehydration influenced the geometry of growth faults. He observed that the geometry of growth faults in the Niger Delta, where the clays are dominantly kaolinitic, differ from those in the Gulf of Mexico, where the clays are smectitic and burial illitization is much more important.

Rule 11. Clay Analysis is a Key to Paleosol Interpretation

Understanding the expression of lowstands is often difficult, particularly where there is no accommodation space due to subaerial exposure, and thus no obvious sedimentary record. Interpretation of paleosols offers a possible answer, but it is necessary to unravel the overprinted paleosol environments that formed during the lowstand and subsequent transgression. Although frequently not depositional, paleosols can be considered part of the lowstand systems tract.

Proper recognition and analysis of paleosols is often critical to interpreting a stratigraphic succession and building a geohistory or a maturation model. However, the analysis has often been based on the most apparent, but relatively ephemeral characteristics of the paleosol.

Presence of a histic horizon (coal), chroma, and even soil micromorphology have been widely used. These may all be valid, but may only be a record of the last thing that happened to the paleosols, not a record of maximum exposure.

Clay mineralogy may be a solution. Clay dogma has it that expandable clays are lost by illitization; generally, this does not begin to happen until well into the oil window. Clays are typically concentrated by weathering; they are also the most conservative element of the soil, and record the most extreme conditions during exposure, while other characteristics (notably organic content and related color) are modified during the subsequent transgression (**Figure 11**).

An excellent example is provided by Midcontinent Upper Pennsylvanian cyclothems (Schutter, 1983; Schutter and Heckel, 1985, illustrated in Figure 8). In the most extreme examples, with no modification by detrital influx, the clay present is derived from the underlying limestone. This is an illite- minor chlorite clay suite, with the clay becoming progressively more weathered upward toward the paleosurface. The resulting paleosol was a vertisol, with expandable clays (illite stripped of K^+) producing the characteristic slickensided peds. The soil was leached of carbonate, sometimes with a calcrete horizon at the base [technically making it an aridisol, since vertisols were not originally defined as including a carbonate-enriched horizon (Buol et al., 1980)]. Notably, although a high degree of K^+ loss sometimes occurred, leaching was never sufficient to result in kaolinite formation, let alone the development of bauxite (alumina). Vertisols also spend a portion of the year above the water table and oxidized; combined with the continuous churning, they do not accumulate organic material.

These paleosols today are dark gray or green, and have autochthonous coals at the top, overlain by marine shales or limestones. This is the record of the subsequent transgression and the rising sea level/water table. The vertisol is overprinted by subsequent soil processes, often resulting in a sulfaquent, produced by a coal swamp and/or coastal marsh, as organic material accumulates. This may also reduce the oxidized iron in the underlying vertisol (some such paleosols are red below and green at the top; thinner ones are now green throughout). Iron sulfides may form as sea water provides the necessary sulfate.

The point is that the clays in the vertisol provide a record of the relative intensity of the exposure; the coal is a transgressive unit. Coals above vertisols do not reflect the lowstand environment, and cannot be interpreted to reflect lowstand conditions. As part of the transgression, they express the transition to highstand conditions. The presence of a vertisol structure indicates that expandable clays were present (although a minimum concentration or threshold level of expandability has not been established). At higher levels of diagenesis and metamorphism, the gap between the amount of expandables originally present and the amount (or lack thereof) currently present could be a measure of the intensity of burial alteration.

While there has been some recognition that the lowstand vertisols in cyclothems have been modified by the ensuing transgression (e. g., Driese and Ober, 2005; Rosenau et al., 2013a, b), the concept has not been broadened and the testament of the clays recognized. The principle of the lowstand record probably extends beyond vertisols and weathered illite; the idea that clays may be a record of those lowstand conditions (including ultra-wet and intensely leached or evaporitic) should be carefully considered.

Clay mineralogy should provide an indication of the most extreme conditions during subaerial exposure. Combined with the features that formed during the following transgression, it should be possible to formulate a more complete analysis of the lowstand. If lateral variability in the paleosols can be established, it may be possible to interpret a complete soil catena, and develop some ideas of the local topography during lowstand. The witness of clays is particularly valuable in non-aggradational settings, where modification of precursor materials is the norm.

The disconnect between lowstand paleosol carbonates and transgressive coals and coal-swamp flora is important to the validity of the analysis of ancient CO_2 levels (Hand, 2017). It may be that the testimony of the clays is important to this, too.

Eagle Ford Example

The Eagle Ford provides an example of how understanding the clay mineralogy may lead to insights into rock properties. Although it has not been systematically studied either vertically or regionally for the information the clays can provide, the random samples of clay data indicate possible patterns (**Figure 11**).

For example, the clays in the Eagle Ford/Woodbine in East Texas are reported to be largely illite, mixed layer illite/smectite, with kaolinite and chlorite (Stoneburner, 2015). This is consistent with a clay suite derived from a nearby landmass, similar to the tropically-weathered clays from the Appalachians and Ouachitas since the Paleozoic.

North Central Texas, in the Metroplex region, represents another facies, apparently distal to the detrital clay facies. The Eagle Ford is more strongly smectitic, apparently reflecting a marked input of volcanic ash (Norton, 1965). This ash may be related to tuffs of southwestern Arkansas, which are reported to be biedellitic, derived from silica-poor alkali volcanics (Ross et al., 1929). On the other hand, Kauffman and others (1977) correlated one of the ash beds with bentonites in the Western Interior, suggesting a possible link to the Late Cretaceous arc volcanism along the western margin of North America.

The detrital influence also disappears across the San Marcos Arch and into South Texas and the Maverick Basin. The reported clays are more strongly illitic. Compared to the detrital belt in East Texas, the clays are reported to have much more illite/mica and less mixed layer clays (Stoneburner, op. cit.). This would be consistent with higher illite crystallinity as a result of slower deposition, but this has not yet been directly demonstrated. Westward, Ca-montmorillonite occurs along with volcanic ash (Pierce, 2014).

As a separate issue, kaolinite is widely reported in the Eagle Ford. However, it seems unlikely that the kaolinite is detrital or authigenic (with the exception of the Eaglebine sediments in East Texas), but rather is diagenetic, forming well after deposition and burial. It is reported to fill microfossils, as well as intergranular pore spaces (Ozkan et al., 2014; McAllister et al., 2015; Ko et al., 2017). The interval is reported to contain abundant volcanic ash layers (Driskill and others, 2012, reported up to 250 ash beds in the Maverick Basin, and over 300 were counted by Ozkan and others, op. cit.); the kaolinite has been associated with some of these (smectitic ashes, noted above,overlap with kaolinitic ashes). However, the apparent analog – kaolinitized volcanic ash in tonsteins in coal seams – formed in highly acidic fresh water environments (Bohor and Triplehorn, 1999; Potter et al., 2005, p. 141-142). Kaolinitic horizons in southwestern Arkansas have been interpreted as altered volcanic ash, but they are in fluvial deposits, associated with lignites (Ross, op. cit.; Hazzard, 1939). Kaolinite is unlikely to form directly in a marine environment, both because of the generally basic conditions, but also due to the high activity of metal ions, particularly Na^+, K^+, and Mg^{+2}. The kaolinite present is often reported as filling voids in microfossils (e. g., Milliken and Day-Stirrat, 2015, Fig. 5B; Denne et al., 2016; Ko et al., op. cit.), characteristic of diagenesis in carbonate environments.

The abundant volcanic ash in the Eagle Ford has been attributed to the volcanoes of the Balcones province (Pierce, 2014; Fairbanks et al., 2016). The Balcones volcanoes were very small, and individually did not persist very long. The Turonian was also only the onset of volcanism, with relatively minor activity until the Coniacian to Campanian, although Ogiesoba and Eastwood (2013) interpreted a few small volcanic cones in the Eagle Ford interval. The Balcones volcanoes have an unusual silica-poor mafic composition, generally described as nephelinites, basanites and phonolites (Barker et al., 1985). They differed from the silica-poor volcanics of southwestern Arkansas in having a much higher content of ferromagnesians. Most likely, they produced explosive phreatic eruptions, as the magma came in contact with sea water, but may have lacked the volatiles necessary to produce a towering eruption column and widespread ash. Debris from these volcanoes would be quartz-free with very little feldspar. An oil-bearing carbonate reservoir associated with a volcano in South Texas is sealed by a nontronitic clay layer (Hutchinson, 1994) (nontronite is a an iron-rich smectite, the type of clay that might be expected with the Balcones volcanoes). In contrast, the ash from the Arkansas volcanoes altered to biedellite.

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Calvin and others (2017) noted that the ashes altered to kaolinite tend to occur relatively close to their putative sources; the kaolinitic ashes also tend to have abundant diagenetic minerals. They concluded that there was likely and original compositional difference, in contrast to the smectitic ashes.

So we have two mysteries, probably related. If the smectitic volcanic ash in the Eagle Ford did not come from the Balcones volcanoes, where did it come from? And what about all that kaolinite?

The smectitic volcanic ash in the Eagle Ford may have come from volcanoes along the subducting margin of the Paleopacific, continuous with those producing the volcanic ash throughout the Western Interior and north central Texas, a possibility considered by Charvat (1985) and Pierce (2014). The Eagle Ford ashes are reported to contain free quartz and feldspar (Ozkan et al., op. cit.; Pierce, op. cit.; McAllister et al., op. cit.; Frébourg et al., 2016), which is inconsistent with the magmas of the Balcones volcanoes. Calvin et al. (op. cit.) noted that the smectitic ashes retain more of the original volcanic minerals than the kaolinitized ashes.

The kaolinite is probably from post-depositional diagenesis, when the pore water chemistry could be modified; it is a diagenetic overprint, and not representative of the original deposition. The kaolinite formation could be attributed to regional pore water characteristics, but on a speculative basis might be related to hydrothermal systems. While the Balcones igneous activity was unlikely to be the source of widespread smectitic ash, the intrusions into the subsea sediments could have resulted in hydrothermal activity, a possible mechanism for kaolinitization. Enhanced maturation of the Eagle Ford, in thermal aureoles around the volcanoes, might be expected, although that has not been reported to date.

A useful analog may be the Miocene Monterey Formation of coastal California. Widespread volcanics altered to smectite (Compton, 1991). With burial diagenesis, the smectite altered to ordered mixed layer illite/smectite and abundant kaolinite and dolomite in some metabentonites. It was suggested that limited K availability resulted in kaolinite, chlorite and possibly late dolomite formation. (Given that the alteration from smectite to kaolinite requires a large addition of Al, that may have been a more important factor.)

The smectitic ash/kaolinitic ash in the Eagle Ford is not a moot issue. While both types of ash may have production issues, the smectitic ashes are more of a problem because of sensitive clays and fines migration; the kaolinitized ashes, not so much (Calvin et al., op. cit.). There is also the issue of what kind of volcanic ash may be expressed as a background input, not expressed as a discrete ash bed, and how that might affect the bulk properties of the mudstone.

In addition to the kaolinite/volcanic ash issue, there is another Eagle Ford issue clays may help to resolve. Eagle Ford stratigraphy, particularly as it relates to depositional history, is problematic. For example, it is not clear if there is an equivalent section in South Texas to the Woodbine interval in East Texas. Significant unconformities are reported in different parts of the section: at the Eagle Ford/Austin contact in East Texas (Hentz et al., 2014), or at the top of the lower member of the Upper Eagle Ford in West Texas (Donovan et al., 2015). Denne and others (2016) interpret the condensed Bouldin Member of the Austin area (across the latest Cenomanian and Early Turonian interval) to be missing in East Texas. Pope and others (2017) noted "cryptic" hiatuses within the Eagle Ford, particularly at the Cenomanian-Turonian boundary interval.

These interpretations are not mutually exclusive. The Eagle Ford "unconformities" may be less regional than implied. Nondepositional intervals may be more common. The evidence for unconformities comes from burrowed hardgrounds, changes in lithology, and biostratigraphic gaps, sometimes associated with surfaces containing intraclastic rip-ups. However, direct evidence of erosion, accompanied by redistributed clastic sediments or irregular surfaces, have not been reported. The Eagle Ford bedding above and below the putative unconformities remains parallel; there is no evidence of irregularities resulting in differential compaction, the biostratigraphic gaps over highs are consistent with increasing bottom currents leading to nondeposition.

The data provided in Donovan and others (op. cit.) may provide a clue. Average depositional rates in the various parts of the Eagle Ford are very low, far below the 10 cm/Kyr estimated by Brett and Baird (1986) needed to prevent shelly fossils from dissolving on the sea bottom. However, the Eagle Ford contains abundant limestones and disseminated carbonate grains, although not uniformly distributed. One answer is that the deposition was episodic, with brief depositional episodes in a background of minimal deposition (such episodicity is a basic principle of sequence stratigraphy, expressed by Campbell, 1967). Local variations in depositional rate can also explain the local expression of volcanic ashes, which may be diluted by deposition in more active areas.

Regionally, the Eagle Ford has been described as having a basal clay-rich interval. This has been interpreted as prodeltaic (Hull et al., 2015), but it does not show directional wedging, coarser grain size, or other sedimentological evidence (McGarity et al., 2014). It is also unlikely that the Eagle Ford was deposited in a shallow restricted basin; the Kirschberg gypsum in the underlying Edwards Group (Wilson, 1990, p. 250) shows that a lagoon would rapidly become hypersaline and precipitate evaporites. Following the idea of McGugan (1965) that thin units persistent over large shelf areas mark relative high stands, these shales, rather than periods of detrital

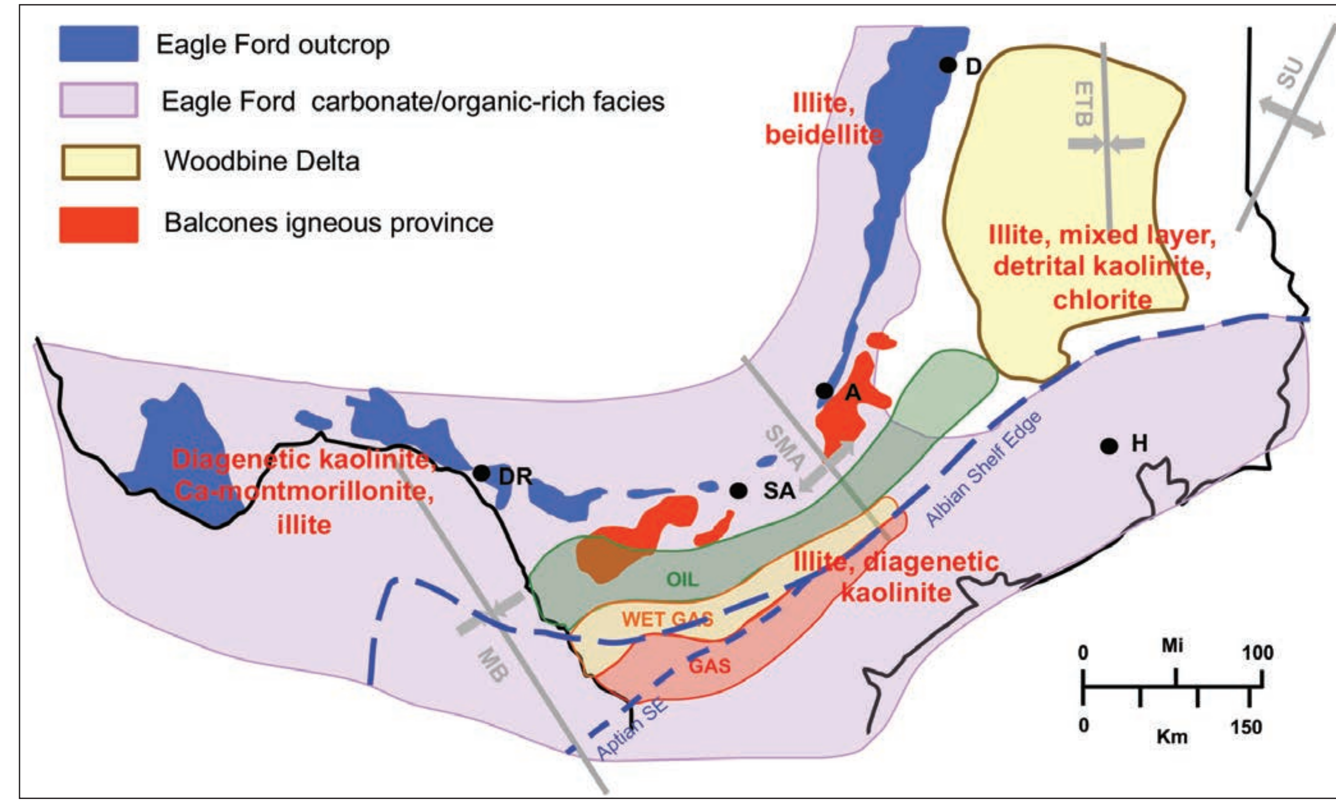

Figure 12. *Eagle Ford clay provinces. Although the Eagle Ford clays have not been systematically studied (so the provinces have no specific outlines), available information supports several conclusions about depositional environments and diagenesis. A=Austin; D=Dallas; DR=Del Rio; H=Houston; SA=San Antonio. Structural elements (gray): MB=Maverick Basin; SMA=San Marcos Arch; ETB=East Texas Basin; SU=Sabine Uplift. The areas labeled "Oil", "Wet Gas", and "Gas" indicate the productive trends within the Eagle Ford. Data from Ewing and Caran, 1982; Ogiesaba and Eastwood, 2013; Chen et al., 2015; Stoneburner, 2015; Denne et al., 2016; Fairbanks et al., 2016.*

influx, could represent periods when depositional rates dropped low enough that carbonate was frequently lost. Brett and Baird (op. cit.) observed that this often happened in shelf successions: the limestone intervals, rather than marking slowdowns in siliciclastics input, actually showed taphonomic evidence of rapid deposition during an event, at least on the upper surface.

The inoceramids of the Eagle Ford may also provide evidence. They sometimes occur in monospecific layers of very thin shells (which are largely prismatic calcite) showing no evidence of abrasion or sorting; breakage is principally due to compaction. These would constitute what Heckel (1972, p. 256-257) described as "whole-shell calcarenites." They occur in deeper water with infrequent high-energy events, and with shells accumulating more rapidly than mud (which may still be abundant, since there is no winnowing).

The evidence is strengthened by gradational features. The Eagle Ford limestones are characterized by being dominated by planktonic foraminiferal packstones to grainstones (which Heckel, 1972, noted was a feature of deposition on the outer shelf). Calcitic inoceramids are present, although sometimes reduced to scattered calcite prisms, while aragonitic ammonites are present only as molds (Fairbanks et al., 2016), suggesting differential dissolution (Malinky and Heckel, 1998). Denne and others (op. cit.) noted that radiolarians were abundant in the medial to distal limestones (where they were replaced by calcite) but rare and pyritized in the interbedded marls, possibly also a function of preferential preservation. They also noted that the foraminifera in the marls were frequently crushed (as opposed to those in the limestones, which were not). Episodic preservation of fossils may also explain why they appear to be restricted to certain layers. Along with the lack of shallow-water algae or carbonate mud, this suggests features of deeper water carbonates recognized by Heckel (1983, p. 743-744).

Thus, the shales and marls of the Eagle Ford mark periods of decreased sedimentation, which sometimes came to a complete halt, resulting in hiatuses (or unconformities). This is consistent with phosphatic hardgrounds (J. A. Breyer, oral comm., 2014), an abundance of volcanic ash layers (Loutit et al., 1988), and the concentration of illitic non-calcareous clays, especially near the base (Eberl, 1978, noted Ca^{+2} inhibited illitization).

Failure of deposition, and the associated surfaces, may be major issues in unconventional resource shales like the Eagle Ford. They

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are frequently altered to hardgrounds, or associated with increased clay content, and thus may be important barriers to fluid flow and fracture propagation.

Clay mineralogy, particularly in the Eagle Ford, may provide a key to understanding these nondepositional intervals. Illite crystallinity would be expected to go up in association with lower rates of sedimentation (Schutter, 2016). The presence of abundant volcanic ash may also be useful. The ash would provide an alien geochemistry and clay mineralogy compared to that which would normally occur locally. Recognition of the relative volume of local clays versus imported clays (assuming a relatively constant background of volcanic ash over longer periods) would produce an index of deposition - sediments would become more "ashy" when local sedimentation slowed. This would provide better evidence of the frequency, intensity, and extent of nondepositional surfaces and zones, and could lead to models of how they would impact development.

In addition to the issue of depositional and diagenetic history and impact on reservoir engineering, the clays present in the Eagle Ford may also impact the hydrocarbons. The catalytic effects of the clays may determine when and how maturation takes place, and the degree of adsorption to the clays (especially in contrast to the carbonate) may govern when and how effectively hydrocarbons are released into pore spaces.

The clay minerals of the Eagle Ford indicate that there is much to learn about how the sediments were deposited, and what might govern their properties. However, they also suggest ways to study and resolve these issues. Detailed comparative sampling, both vertically and laterally, might help resolve issues on depositional environments, their timing and relationships. This could, in turn, lead to better prediction of rock properties and continuity, as well as better basin modeling.

Permian Basin Example

The Upper Pennsylvanian and Lower Permian strata of central North America have several distinctive clay suites. These reflect the depositional environments, the climates and the provenance of the region. They occur in predictable patterns, and thus can be used to unravel the stratigraphy and probable petrophysical properties of the rocks.

The clay suite derived from the Appalachian-Ouachita thrustbelt is characterized by illite and stripped illite/mixed layer clays, with

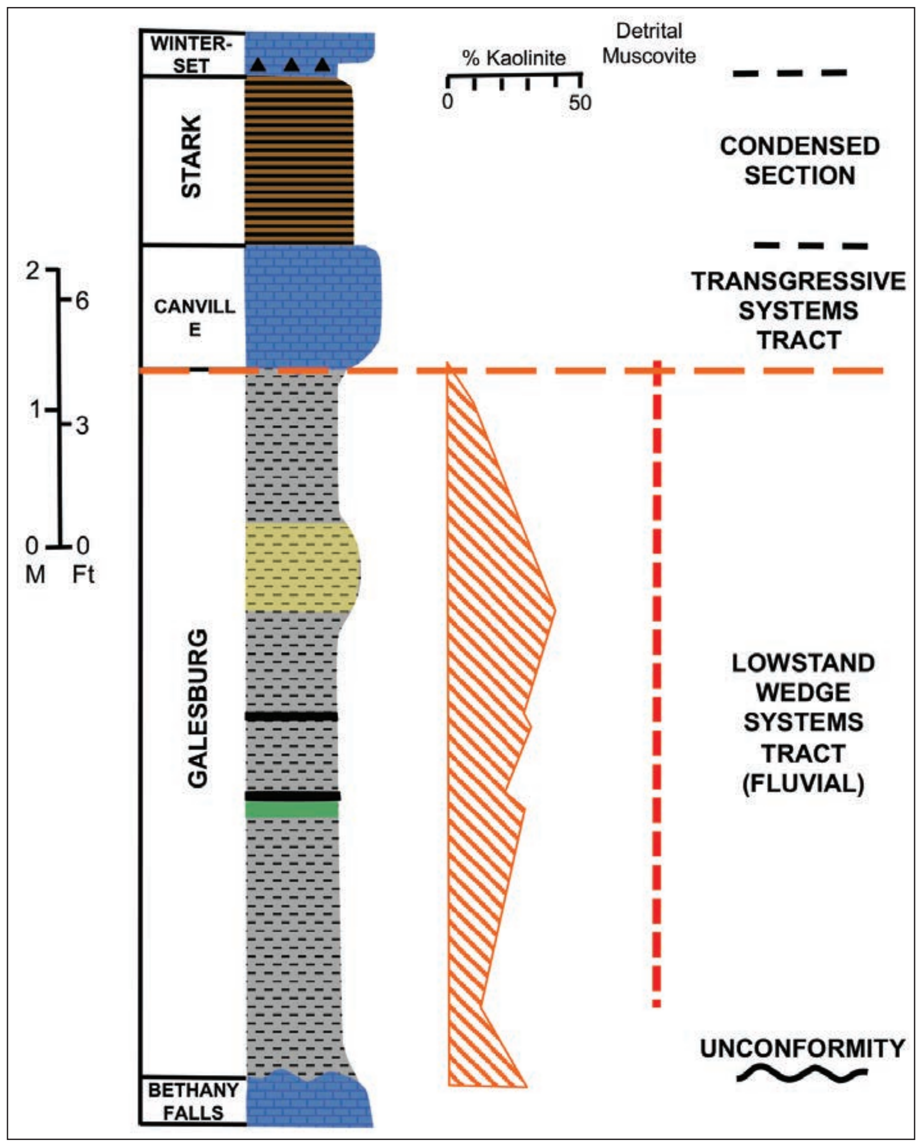

Figure 13. *Expression of the kaolinite-muscovite detrital suite in southeastern Kansas (Galesburg Shale and Dennis Formation near Stark, southeastern Kansas). The fluvial-deltaic sediments of the lowstand wedge systems tract include these clays, although it is dominantly degraded illite-subordinate chlorite. It is generally noncalcareous, with local coal stringers. Note that the kaolinite-muscovite suite abruptly disappears with sea level rise, and is replaced by the local illite-chlorite suite. Also note that the basal Winterset limestone is silicified, directly above the radiolarian-bearing phosphatic Stark Shale. Compare the Galesburg of this section (particularly the clay suite) to the Galesburg of Figures 7 and 8. (Figure modified from Schutter, 1998, Fig. 7.)*

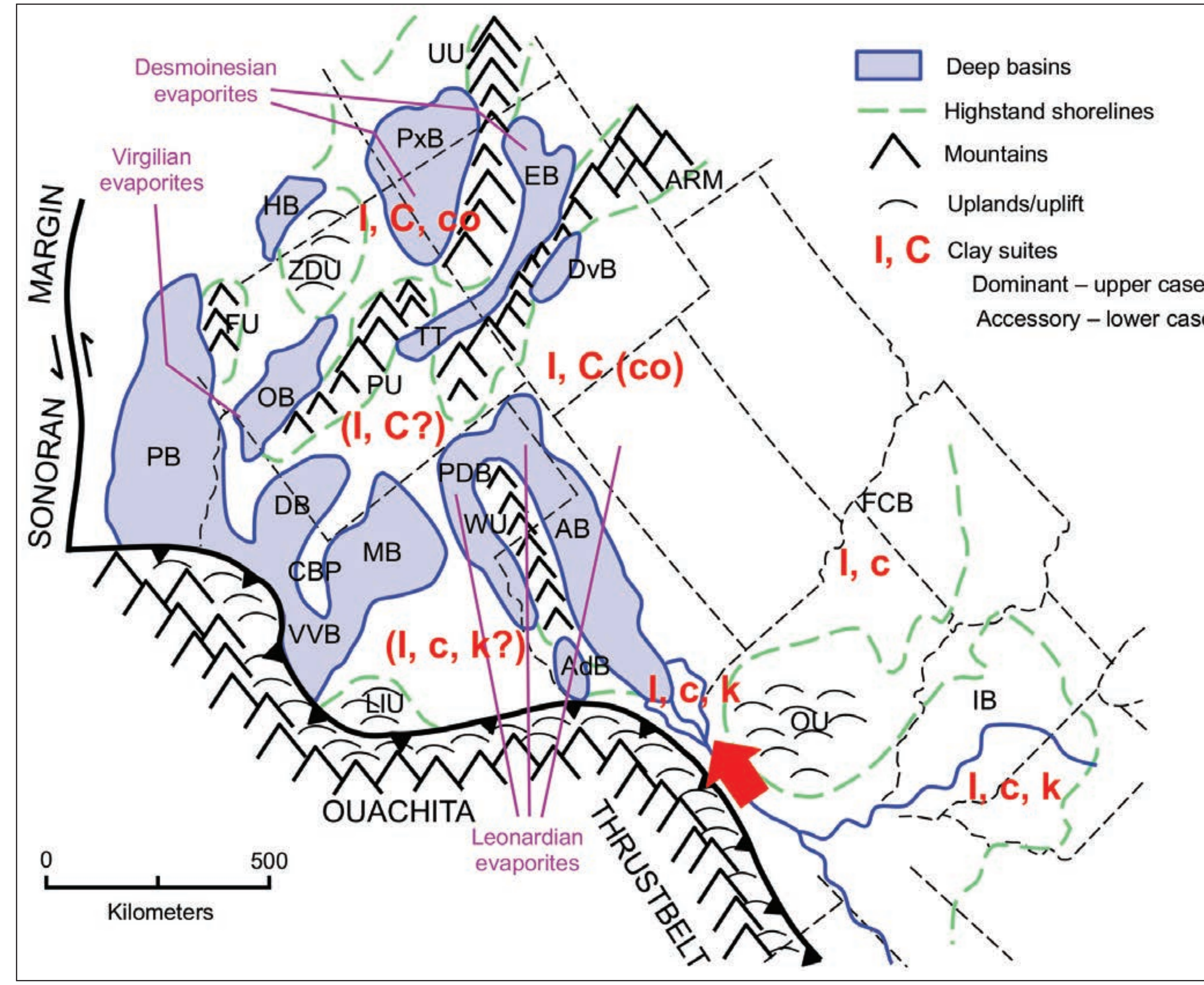

Figure 14. *Figure 14. Distribution of clay suites in the Upper Pennsylvanian-Lower Permian strata of central North America. Different areas have different clays suites, reflecting different environments and sources. Probable depositional environments and diagenetic history can lead to improved prediction of hydrocarbon systems and petrophysical properties.*

- *The clay suites are indicated by the dominant and accessory clays; upper case indicates dominant clays, and lower case indicates accessory clays. I=illite and stripped illite (random mixed layer); C=chlorite; K=kaolinite; co=corrensite.*
- *Note the clays derived from the Appalachian-Ouachita thrustbelt are illitic with subordinate chlorite and kaolinite (this includes the Illinois Basin); these reach the eastern end of the Anadarko Basin (indicated by the arrow), spreading into a large deltaic system during lowstand.*
- *This clay suite would be expected for the Eastern Shelf in Texas as well. This contrasts with the clay suite in the Forest City Basin and the northern Midcontinent, which generally lacks detrital kaolinite. The clays sampled from the Paradox Basin and the Ancestral Rockies are illitic with high concentrations of chlorite; corrensite has been reported associated with evaporitic conditions; kaolinite is absent. A similar clay suite might be expected on the western side of the Delaware and Midland basins.*
- *The map is oriented to reflect the tilt of North America at that time. Conventional paleomagnetic interpretation places the paleoequator, with everwet conditions, about the position of the Ouachita thrustbelt. However, the clay suites, along with thick caliche horizons in paleosols, phosphatic upwellings, bedded evaporites, and widespread carbonate deposition all indicate a considerably higher and drier paleolatitude.*
- *Map modified from Greb et al., 2003; Algeo and Heckel, 2008; and Leary et al., 2017; clay data from Schutter, 1983.*
- *AB=Anadarko Basin; ARM=Ancestral Rocky Mtns; AdB=Ardmore Basin; CBP=Central Basin Platform; DB=Delaware Basin; DvB=Denver Basin; EB=Eagle Basin; FU=Florida Uplift; FCB=Forest City Basin; HB=Holbrook Basin; IB=Illinios Basin; LlU=Llano Uplift; OB=Orogrande Basin; OU=Ozark Uplift; PDB=Palo Duro Basin; PxB=Paradox Basin; PU=Pedernal Uplift; PB=Pedregosa Basin; TT=Taos Trough; UU=Uncomphagre Uplift; VVB=Valverde Basin; WU=Wichita Uplift; ZDU=Zuni-Defiance Uplift*

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subordinate chlorite (typically 10-20%) and kaolinite (typically 10-15%). The illite is not highly weathered, but apparently reflects relatively rapid erosion and transport. The clays are generally associated with detrital muscovite. Significantly, this clay suite characterizes the deltaic complex of the river system draining the Appalachian-Ouachita foredeep, depositing sediments in the eastern end o the Anadarko Basin (having largely filled the Arkoma Basin by the Late Pennsylvanian) (**Figure 13**). This clay suite might also be expected on the Eastern Shelf of the Midland Basin, shed from the Ouachita thrustbelt.

In contrast, the Upper Pennsylvanian of the Forest City Basin and the (now) northern portion of the Western Interior Basin is characterized by an illite (including stripped illite/random mixed layer)-subordinate chlorite suite. (An example is discussed in **Figures 6-8**.) The illite is typically highly degraded, particularly in paleosols. Detrital kaolinite and muscovite are generally lacking. This clay suite is quite different from the clays from the Appalachian-Ouachita thrustbelt, which occur in eastern Oklahoma and southeastern Kansas, as well as in the Illinois Basin. That illite-chlorite-kaolinite clay suite also characterizes the Middle Pennsylvanian (Desmoinesian) in the Forest City Basin, along with abundant coals. The coals and the clay suite disappear at the Middle-Upper Pennsylvanian boundary in the Forest City Basin. Following that, there is not evidence of effective spillover from the Illinois Basin, and local conditions do not favor kaolinite formation.

A third possible clay suite (more anecdotal, since it was not a focus of the original study) seems to be present in association with the uplifts of the Ancestral Rockies and similar uplifts. These are characterized by illite (again, not extensively degraded) and abundant chlorite (often over 30% of the clays). Kaolinite is absent. Corrensite was found in the clays from the Paradox Basin, and has been reported associated with evaporites from western Kansas. A similar clay suite might be expected along the western and northern margins of the Delaware and Midland basins (**Figure 14**).

The clay suites reflect the changing climate and depositional environments, as North America drifted southward during the Pennsylvanian and Permian. During the Middle Pennsylvanian, deposition across the Western Interior (including the Forest City Basin) and Eastern Interior (including the Illinois Basin) basins were dominated by fluvial siliciclastics with thick coal seams, characterized by clays including abundant kaolinite. These abruptly disappeared at the end of the Desmoinesian; the mighty coal swamps vanished around the world, except in China. Deposition in the Western Interior became much drier, with widespread carbonate deposition and a lack of sandy siliciclastics. Offshore, there were vigorous bottom currents and upwellings concentrating phosphate in organic-rich shales. Paleosols often included thick caliche horizons. The clays were locally derived and strongly weathered, at least seasonally well-drained and oxidizing (Schutter and Heckel, 1985).

In the high-frequency eustatic cyclothems of the Pennsylvanian and Permian, the shifting environments could be seen in the clays. As noted in the section on illites (**Rule 4**), lowstand weathered illites alternated with highstand highly crystalline marine illites. But perhaps more dramatic was the alternation in southeastern Kansas and eastern Oklahoma. There, during lowstands, the kaolinite-bearing clays from the Ouachitas and even the Appalachians were present, spread in lowstand deltaic complexes. With rising sea levels, these clastics were trapped in distant estuaries, and only local clays were available for highstand deposition. It was like an on-off switch.

A similar situation may apply to the Midland and possibly the Delaware basins. Lowstand clastics may cross the Eastern Shelf, accumulating in the deep basin. During the highstands, only local clays would be available. The pattern of alternating clay suites would permit the development of a detailed stratigraphic framework, providing a better exploration model.

In addition to recognizing depositional facies, it is petrophysically important. Diagenesis is a function of the initial components; the clay mineralogy strongly affects the diagenetic pathways taken. If two different clay suites are interbedded, it wil be important to know that. Contrasting clay suites can have different physical and chemical properties and follow different diagenetic pathways with burial. They also make assumptions about baseline clays (for petrophysical analysis) suspect.

Note that none of the clay suites found included significant smectite, at least of the high-silica types cited in traditional illitization models from the Gulf Coast. Thus, large volumes of silica are unlikely to have been released for cementation. There is no evidence that such clays were abundant anywhere in the basin. Diagenesis would follow different pathways, perhaps dependent on the mineralogy of the individual beds.

Implications for the Interpretation of Clays (How)

One of the most significant problems in the interpretation of organic-rich mudstones is the identification of surfaces of non-deposition or hiatuses. Clay mineralogy, particularly illite crystallinity, may provide one of the most direct ways to find them. In conjunction with other methods (e. g., paleoecology, taphonomy, petrology, authigenic mineralogy) it should be possible to identify them; testing with an inverse geohistory model (Schutter, 2016) should result in a robust model.

Sample preparation is an issue. Grinding of samples is generally frowned on with clays, because the clay structures can so readily be disrupted along the basal 001 cleavage plane; powdered samples are limited, and cannot be subjected to the range of procedures necessary to adequately evaluate the clays. Oriented clay samples, where the clays are settled onto flat plates, are far preferable. The clays settle onto the 001 cleavage surface, and can be treated to permit better analysis (both in mineralogy and illite crystallinity). Being able to evaluate illite crystallinity not only improves understanding of depositional environments and stratigraphy, but also opens the possibility of an effective tool for resolving structural problems.

Środón and others (2001) discussed quantitative analysis of whole rock samples from XRD, and concluded that it was accurate based on the non-basal reflections of the various clays. However, the issue is still the quantification of weathered clays (like stripped illite), which have broad, fuzzy peaks, making them difficult to quantify for comparative purposes. More research is needed.

Clays can be recovered from all lithologies; sometimes by simple disaggregation, sometimes with the help of various chemicals. Theoretically, some of these chemicals could damage or alter the clays; empirically, that happens less than might be expected, both because clays are generally relatively stable, but also because processing generally does not take very long. (If in doubt, test.)

A helpful aspect of clay study is that clays are generally not redox-sensitive (although iron-bearing clays may be). Chamley (1989) argued that in strongly reducing environments, there was evidence that smaller, more poorly crystallized clays were preferentially destroyed, particularly smectites and mixed layer clays. However, he also noted that clay degradation occurred very close to the sediment-sea water interface and not after significant burial. It is not clear how this would influence clays if deposition took place in brief, infrequent intervals. Still, the changes in clay mineralogy and characteristics (such as illite crystallinity) may provide a different insight into deposition than the organic matter does.

Another virtue of recovering clays from all lithologies, and not just the shales and mudstones, is that it is possible to determine if the larger system is open or closed, since there would be evidence of diagenesis in the more porous and permeable intervals. Clays in closed rocks might be expected to more closely reflect depositional environments, while those in open rocks would record diagenetic processes, too. Howard (1987) suggested that clays in sandstones could be more illitic than clays in shales, as the clays in sands had more access to K^+. Coulton-Bradley (1987) added that interbedded shales would have higher fluid pressures, which could bleed off in the sands. Eslinger and Pevear (1985) noted that shale diagenesis tends to be largely isochemical, with limited transport in or out.

As noted above, implying relative abundances of clays is problematic. It may be more justifiable if it is done within one sample set, where the clays all come from one setting and are all subjected to the same procedures. Relative abundances between similar samples, establishing trends, has some validity. When trying to compare to other studies, done in other places with other methods, it would be reasonable to repeat a series of samples from the previous study, to establish the amount of variability between studies for calibration purposes.

Assuming that one clay sample adequately characterizes the entire stratigraphic unit is generally a risky proposition, unless the rock is truly deltaic or homogenized by complete burial diagenesis. This is particularly true in respect to illite crystallinity, which may change progressively or abruptly. If possible, clay sampling should be done with this in mind. (Eslinger and Pevear, 1985, suggested using cuttings, rather than core samples, because it would average out the "noise" of fluctuating illite/smectite percentages. That "noise" is probably the signal from the depositional environment.) Building a petrophysical or diagenetic model without accounting for the range of clay variability may be risky behavior.

Another consideration would be to do two or more preparations from each sample, with the object of getting different size fractions. This would help identify any possible size bias in the bulk clay mineralogy, and might be useful in identifying possible diagenetic clays.

The "signal-to-noise" ratio is clearly one of the issues facing the quantitative interpretation of clays. How reliable are individual clay data points? Today, the answer is largely unknown; virtually no section has been sufficiently sampled and analyzed to get an idea of the variation. **Figure 7** illustrates how this might be approached, with a standard deviation analysis of the data. The statistical mean appears to be very robust, but individual data points, scattered within the standard deviation envelope, may be more suspect. More variation might be expected with weathered or outcrop samples than with deep marine or core samples. At least until local variation is understood, redundant samples might be in order. Ultimately, the best approach may be to incorporate clay analysis into an integrated study, where results can be compared to other methods.

Clay studies can be improved by examining correlative sections on the basin margin, where the effects of diagenesis and burial are minimized. This will help to assess what the original clays might have been, providing a qualitative indicator of how they have changed further into the basin. The process may also help to recognize possible successions, helping to recognize similar patterns with a burial-related diagenetic overprint.

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The current processing of whole rock samples (organic-rich shales and otherwise) is deceptively inadequate for effective evaluation of clays, generally providing less information than implied. As noted above, both standard XRD and XRF have important shortcomings, mainly based on an oversimplified concept of clay mineralogy.

Important information can be gleaned from the clays, beyond simple XRD identification. Detailed structural information can come from oriented samples that can be subjected to heating and glycolation, which may reveal patterns within the depositional environment and diagenetic history. Data on clays can also be gleaned from geochemical (such as cation exchange capacity), differential thermal analysis, isotope, microprobe, and micromorphologic studies.

Chemostratigraphy often reaches conclusions about why the relative concentrations of elements vary; less often discussed is how those concentrations vary. It is seldom considered that the variation may be a secondary phenomenon, dependent on the distribution of other parameters. For example, the concentration of uranium is not a simple measure of the redox state of the bottom sediment, nor is is a simple function of the amount of organic material present. Swanson (1960) showed that humic (Type III) organics have a higher affinity for uranium than marine (Types I, II) organics. Thus, uranium concentration may be a reflection of the organic matter present, which may in turn reflect an onshore-offshore gradient (or degradation gradient). Similar relationships might be expected for other elements, such as vanadium and molybdenum. Thus, it matters where the elements (particularly the trace elements) are concentrated. Quartz and calcite are unlikely sources of significant variation. Feldspars are slightly more so, but are normally volumetrically insignificant. The principal sources of variation in organic-rich mudstones are the organics and the clays. Understanding the clays that are present, and how they vary, is a vital component for interpreting the significance of elemental variation.

Analysis of groundwater and formation water has long used major ion activities to indicate what sort of lithology impacted the water quality. This included the identification of argillaceous rocks in the system. More detailed aanalysis (particularly of the cations) may provide evidence of the dominant clays in the sytem; they may also provide evidence of what is happening diagenetically. Notably, water samples may provide evidence of conditions over a large volume, and not just around the immediate well bore.

The clays present, and their diagenesis, may have economic value in their own right. In several instances, oil-field brines have been observed to have elevated concentrations of lithium, and it has been proposed that they could be exploited as a Li source. Generally, the model proposed is that the Li-rich brines formed in continental alkaline playas, which are the dominant modern source for Li. However, an alternative model would be that illitization of Li-rich smectites would eject the Li^+ in favor of K^+, much as illitization of montmorillonite ejects Na^+. (Even with this model, the smectite may have acquired its Li in an evaporitic environment.) Either model could be applicable to the Li-enriched brines from the Norphlet and Smackover (Palmer and Gabitov, 2017); the diagenetic model would seem to be more applicable to the Li-enriched brines in the Marcellus (Glazer et al., 2017). Detailed analysis of cations present may be particularly interesting in this respect.

Clay mineralogy may also have an impact on the natural fractures in a mudstone. Gale (2017) observed that natural fractures probably grow by chemically assisted propagation; this would be dependent on the geochemistry of the sediment and the precise clay species present, and how they respond to progressive diagenesis.

Given that it is possible to interpret the clays expected, and the diagenetic changes that occur under regular conditions, it should be possible to incorporate these changes into basin modeling. Illitization, as well as burial diagenesis of other clays, and the appearance of the various clay polytypes, should be built into a basin model, and possibly related to hydrocarbon maturation and migration. The proportion and type of illite (true illite vs "stripped" illite, for example) makes a difference. Understanding the clays present may help with maturation and migration modeling (based on the organic matter adsorption properties, the catalytic properties, and water and ion expulsion of the clays present). This may lead to porosity/cement evolution and prediction. It should be possible to predict not only what clays would be expected at a given point in a basin, but also to estimate what kind of engineering issues might be present as a result. The physical and chemical properties of the clays present, and in what proportion, will impact issues such as sensitive clays, fines migration, and the possibility of scale formation.

Implications for the Interpretation of Clays (Why)

Understanding where and why particular clays with specific properties may be present is important to many geological and economic issues (**Table 1**). Questions can be answered with precision, modeled and predicted, although the data base is still relatively small. It is important to realize that all these applications do not exist in discrete silos; comparison with and learning from other applications can vastly improve understanding.

For example, understanding clays, their properties and distribution are critical to many petrophysical evaluations. In many calculations, the clays are assumed to have uniform properties and compositions. It is also assumed that a single clay or clay suite is present, and that it doesn't change abruptly. To the extent that these assumptions are not valid, the petrophysical results are suspect. Consider the potential impact if a highly illitic marine shale, with very high levels of K, is selected as the V100 end member, while a sandstone with a kaolinite-mixed layer clay suite is the low end member. Vclay calculations would consistently underestimate the amount of clay present. (This applies to the Midcontinent Pennsylvanian and may apply to the Permian Basin as well, as discussed in the example.) However, proper analysis of the clays may not only resolve these issues, but provide new avenues for petrophysical analysis.

Recognizing the variability, sometimes abrupt, of clay mineralogy can strongly impact the interpretation of diagenetic phenomena. Unless some concept of the potential variability of the clays is in hand, it isn't possible to unequivocally attribute an observed diagenetic change to burial or composition. Thus, a valid diagenetic study needs to include an assessment of the likely variability of the clays present, and if a strong environmental signal might impact the clay suites.

Table 1. *Clay Applications*

Depositional Environments
• Sequence stratigraphy (rate of deposition)
– Unconformities
– Flooding surfaces
• Paleosols
• Paleoclimate
– Sensitive clays (evaporites)
• Sequestration of organics
• Provenance
• Facies
Diagenesis
• Basin modeling
• Porosity evolution
• Alteration of minerals
• Release of Si for cements (illitization), water, Fe
• Clay polytypes
Ground/formation Water Quality
Structural Interpretation
Petrophysics
• Validity of Vclay models
Engineering Issues
• Impacted by clays and clay-derived properties
– Sensitive clays
– Fines migration
– Scale from clay reactions
– Overpressure
Clay-related Mineral Resources
• Lithium, other metals released by diagenesis
• Industrial clays
• Catalytic clays
• Specialty clays
– Food, drug, cosmetics addititves

Conclusions

Physical stratigraphy and sedimentology have been widely used to interpret mudstones (e. g., Lazar et al., 2015). Petrophysical methods are derivative of these interpretations. Paleontological methods (including biofacies and taphonomy) constitute a second line of evidence. The study of clays is a third principal way to study mudstones and their context.

A principal purpose of this paper is to suggest that clays are important components of shales and mudstones, but also of carbonates, coarse siliciclastics, and other sedimentary rocks. Study of the clays can answer a range of questions, engineering as well as geological. Not only that, but clays are systematic and relatively easy to understand.

Clays are not complex, chaotic elements of sediments, nor are they simplistic, homogenized components that are all essentially the same. There are basic principles for understanding why they are as they are, and systematic analysis of the rocks can bring out this information. An enormous amount of valuable data can be collected with the proper approach.

Clay analyses can be incorporated into environmental models for exploration and development purposes. They can be very powerful, especially in a data-rich environment. Unfortunately, that type of data is rarely collected on clays. They need to be studied in context (as part of integrated studies). Unfortunately, they rarely are.

You may argue that much of this discussion is undocumented assertion. That may be true, but the point is that there has been so little systematic study of where clays occur, why, and in what condition there is little to go on but generalities. It is the job of future investigators to establish the broad applicability of these assertions, which are at least supported by anecdotes. ■

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Government Update

by ***Henry M. Wise, P.G. and Arlin Howles, P.G.***

If you'd like the most up-to-date Texas rules, regulations, and governmental meeting information we direct you to the HGS website to review The Wise Report. *This report, which comes out as needed but not more often than once a week, offers the most up-to-date information that may be of interest to Texas geologists.*

AGI Geoscience Policy Monthly Review (July 2018)

EPA Holds Public Hearing for Proposed Rule on Strengthening Transparency in Regulatory Science

The Environmental Protection Agency (EPA) held a twelve-hour public hearing on July 17, 2018 to hear oral comments on the proposed rule entitled "Strengthening Transparency in Regulatory Science." The proposed rule would require the EPA to only use scientific studies with publicly available data in developing regulations, unless the EPA administrator exempts these requirements on an individual case-by-case basis for significant regulatory decisions that are based on studies with protected, private data.

More than one hundred preregistered individuals – many representing non-profits, coalitions, governments, businesses, and universities – were allotted up to five minutes to present testimony to a panel of two EPA representatives. Critics of the proposed rule significantly outnumbered supporters at the public hearing. Representatives Paul Tonko (D-NY-20) and Suzanne Bonamici (D-OR-1) testified vehemently against the rule, which they regarded as an "attempt to circumvent the legislative process…[and] to limit research…that supports critical regulatory action."

While the initial comment period for the April 30, 2018 proposed rule was limited to thirty days, which is the minimum number of days required for comments on a proposed rule, the EPA extended the comment period until August 16, 2018 after the agency received extensive public feedback indicating that more time was needed for stakeholders to adequately respond to such an impactful rule. On June 28, 2018 the EPA's Science Advisory Board (SAB) sent a letter to then Administrator Scott Pruitt urging the agency to fully consider public comments and to request, receive, and review scientific advice from the SAB before revising or finalizing the proposed rule. By the time of the hearing, over 200,000 comments had been received on the docket with more yet to come.

Florida Representative Carlos Curbelo Introduces Controversial Carbon Tax Bill

Representative Carlos Curbelo (R-FL-26) introduced the first Republican carbon pricing bill in nearly a decade on July 23, 2018, breaking with the party's long-standing general opposition to such policies. The proposal, called the MARKET CHOICE Act (H.R. 6463)—an acronym for the Modernizing America with Rebuilding to Kick-start the Economy of the Twenty-first Century with a Historic Infrastructure-Centered Expansion Act—seeks to reduce greenhouse gas emissions by imposing a federal carbon tax, and to use the revenue to fund infrastructure modernization.

The MARKET CHOICE Act would put a $24-per-ton tax on carbon dioxide emissions starting in 2020, which would increase 2 percent above inflation each year. The bill directs 70 percent of the revenue to go to the Highway Trust Fund, with an additional 10 percent going to grants for low-income households and 5 percent to coastal flooding mitigation and adaptation projects. The remaining revenue would go to various research and development (R&D) efforts, such as ARPA–E, carbon capture and storage, battery storage, and direct air capture projects, and for a fund to assist any energy workers that may be displaced by effects of the tax. The bill would also impose a rolling, performance-based moratorium on the federal government's ability to finalize and enforce regulations on greenhouse gas emissions (except for methane emissions) from stationary sources covered by the tax.

Representative Curbelo, who is a co-chair and co-founder of the House Climate Solutions Caucus, joined the Columbia University Center for Global Energy Policy (CEGP) to discuss the introduction of his new legislation on the day of its release. According to an analysis led by CEGP scholars posted on July 19, 2018 Representative Curbelo's proposal would reduce economy-wide net greenhouse gas emissions by 27–32 percent by 2025 and 30–40 percent by 2030, compared to 2005 levels. This would outpace the United States' nationally determined contribution to the Paris Agreement of 26–28 percent by 2025, although President Donald Trump announced his intent to withdraw the U.S. from the Paris Agreement last June.

The MARKET CHOICE Act was introduced just days after the House voted on and passed an anti-carbon-tax resolution from Majority Whip Steve Scalise (R-LA-1), expressing "the sense of Congress that a carbon tax would be detrimental to the United States economy." Representative Curbelo was among six Republicans who voted against the resolution, while seven Democrats strayed from party lines and voted in favor. After the vote on the resolution, Representative Curbelo told reporters that while his plan would implement a carbon tax, it would also repeal the jet fuel excise tax and the gas tax, "which is regressive and is unfair to low- and middle-income Americans who drive

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traditional vehicles." He said that his proposal would generate $700 billion in revenue over a decade for infrastructure investments, and he intends to pitch the bill to the White House as a potential way to fund President Trump's infrastructure plan.

House Subcommittees Hold Joint Hearing to Discuss Fossil Energy Technology Developments

On July 17, 2018 two subcommittees of the House Science, Space, and Technology Committee – the Subcommittee on Energy and the Subcommittee on the Environment – held a joint hearing to discuss the future of fossil fuel as a primary energy source. The hearing also focused on the Department of Energy's (DOE) partnerships with industry groups to develop technology that aids in the management of carbon dioxide.

The hearing opened with statements of support for the DOE-funded fossil energy technology research projects and highlighted some their recent developments. Representative Marc Veasey (D-TX-33) and Science Committee Ranking Member Eddie Bernice Johnson (D-TX-30) highlighted the Fossil Energy Research and Development Act (H.R. 5745), which they introduced with Representative David McKinley (R-WV-1) in May to reauthorize the DOE's Office of Fossil Energy and expand its research on carbon capture, sequestration and utilization technologies. Energy Subcommittee Chairman Randy Weber (R-TX-14) emphasized his support of carbon utilization and energy production technologies, such as a 3-D printed polymer developed at the Lawrence Livermore National Laboratory (LLNL) that converts methane into methanol.

During witness testimony, Dr. Roger Aines, Chief Scientist of the energy program at LLNL, highlighted DOE funded fossil energy technology projects, and emphasized the importance of national lab research-industry partnerships to integrate technological advancements into the fossil energy industry. Dr. Klaus Brun, Machine Program Director at the Southwest Research Institute, answered questions from committee members about the development of supercritical carbon dioxide power cycles, which replace steam and air used in conventional power plants with carbon dioxide. Brun explained that this development increases efficiency by 3 to 5 percent in conventional steam plants and is "on the verge of commercialization" with a 10 megawatt utility scale power plant opening in 2020.

Representatives Johnson and Suzanne Bonamici (D-OR-1) voiced objections to the proposed fiscal year (FY) 2019 budget cuts that would slash the DOE's fossil energy research and development activities by 31 percent. Representative Bonamici also remarked that "this administration has sent inconsistent messages about fossil energy technology" due to their conflicting agenda of supporting "clean coal" while proposing cuts to research that focuses on ways to make coal production cleaner.

Senate Committee Discusses U.s. Foreign Dependence on Critical Minerals

On July 19, 2018 the Senate Committee on Energy and Natural Resources convened a hearing on critical minerals—the fifth hearing on the subject in almost as many years, according to Chairwoman Lisa Murkowski (R-AK). The hearing was held to review the Department of the Interior's (DOI) recently published final list of critical minerals, which are minerals required for basic civilian and/or military manufacturing and with a supply chain vulnerable to disruption. These critical minerals are used in a broad range of products essential to the economy and national security of the United States—from iPhones and fighter jets to practically every form of modern transportation.

In December of 2017, President Donald Trump released Executive Order 15817 directing DOI, in coordination with other federal agencies, to prepare a list of critical minerals and an interagency report addressing the United States' vulnerability to disruptions in the supply of those minerals. As outlined in the Executive Order, the report must include a strategy to reduce the nation's reliance on critical minerals, an assessment of recycling and reprocessing technology development, options for investment and trade through reliable sources, a plan to improve the topographic, geologic, and geophysical mapping of the U.S., and recommendations to streamline the mining permitting process.

Steven Fortier, director of the National Minerals Information Center at the U.S. Geological Survey (USGS), testified that the USGS Mineral Resources Program has already submitted a report on a proposed mapping plan that will be wrapped into the larger report stipulated by the executive order. The new generation of geological, geophysical, and topographic maps, part of the administration's proposed Three Dimensional mapping and Economic Empowerment Program (3DEEP), would be compiled at a scale appropriate for assessing critical mineral resources for mining, which would also support work on other natural resources and urban planning. Fortier also clarified that the current critical minerals list is finalized but will be revisited periodically in the future, although a specific timeline has not yet been established.

In her opening statement, Senator Murkowski highlighted the "serious but needless" vulnerability in the U.S. critical mineral supply chain. Senator Murkowski stated that the U.S. supplies of twenty-one critical minerals are entirely imported and emphasized that the nation's dependency on foreign imports has doubled in the past few decades. Much of the U.S. supply of critical minerals comes from China, a point of concern addressed at the hearing by Senators Murkowski and Ron Wyden (D-OR), who highlighted the nation's current trade tensions with China and China's previous record of selectively blocking rare earth element exports to Japan during a dispute in 2010. Senator Wyden also highlighted the Critical Minerals Policy Act of 2013 (S. 1600), a bill which he cosponsored in a previous session of Congress, as an example of bipartisan legislation seeking to address this issue. Senator Murkowski also expressed concern over the administration's fiscal year 2019 request to eliminate funding for the Department of Energy's Critical Minerals Institute.

During the hearing, some committee members and witnesses suggested emerging components of the U.S. critical mineral supply portfolio to include reclamation from coal slag, improved recycling, and the development of alternative technologies less dependent on critical minerals. Dr. Roderick Eggert of the Critical Materials Institute advised that, while there are not currently many systems in place for critical mineral recovery, now is the time to develop collections systems, sorting systems, and processing technology so that recycling can play a larger role in the future. Furthermore, witnesses noted the importance of improving mineral processing capacity in the United States, since better mining capacity and other alternatives alone would not resolve the vulnerability of the nation's critical mineral supply chain. Witnesses also discussed the need to support a robust and capable workforce.

House Science Committee Moves Forward with the Space Weather Research and Forecasting Act

The House Committee on Science, Space, and Technology held a full committee markup on July 24, 2018 to consider the Space Weather Research and Forecasting Act (S. 141), which passed the Senate by unanimous consent in May 2017.

Variations in space weather, caused primarily by changes in the charged particles emitted by the Sun, threaten the electrical power grid, telecommunication networks, and satellite and aircraft operations. S. 141 would direct the Office of Science and Technology Policy (OSTP) to coordinate interagency research and monitoring efforts to better understand space weather events. It would also require OSTP to work with the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the Department of Defense (DOD), to develop sustainable observing, modeling, and forecasting capabilities.

During the House markup, committee members offered three amendments to the space weather bill—two of which were agreed upon by a voice vote. Representatives Ed Perlmutter (D-CO-7) and Mo Brooks (R-AL-5) introduced an amendment that designates the National Space Council as the coordinating force behind federal space weather activities, rather than OSTP. Additionally, their amendment requires collaboration with the private sector, adding that "the federal government should, as practicable, obtain space weather data and services through contracts with the commercial sector, when the data and services are available, cost-effective, and add value." With this amendment, the bill would establish a pilot program through NOAA to reward up to $6 million a year in contracts to commercial sector entities to determine the viability of obtaining commercial space weather data from these providers. Another amendment offered by Representative Perlmutter and agreed to by the committee adds language that emphasizes the need for space weather observation and forecasting for deep space exploration.

Ranking Member Eddie Bernice Johnson (D-TX-30) was among a select few members on the committee who opposed the amendments due to their resulting differences to the Senate version of the bill. Ranking Member Johnson offered an amendment to replace the text of S. 141 with the Space Weather Research and Forecasting Act (H.R. 3086), which was sponsored by Representative Perlmutter in June 2017 and closely resembles the Senate's space weather bill; however, the change was defeated by a vote of 19 to 13, with Representative Perlmutter voting against Ranking Member Johnson's proposal to replace S. 141 with the text of his own bill. ■

Remembrance

Jay Owen Gallagher
1931-2018

Jay Owen Gallagher passed away on Tuesday, the 4th of September 2018. He was born in Garden City, Long Island, New York. He was a graduate of The Admiral Farragut Academy. Received his geology degree from University of Illinois and received his Masters from the University of Colorado.

Jay worked for The Superior Oil Company in locales of Libya, South Africa and opened the London office for Superior. He started his own consulting firm Gexco and was also President and CEO of Texoma Production Company (Midcon Corporation). He was also very proud to be associated with the CLK Partnership, Houston/New Orleans.

He is survived by his wife Louann Clark Gallagher and brother in law John W. Clark Jr., his son Thomas Martin Gallagher and his Godsons Jax Fisher and Houston Rentz of Houston Texas..

HGS Welcomes New Members

New Members Effective September 2018

ACTIVE MEMBERS	EMERITUS MEMBERS	STUDENT MEMBERS
John Dodds	Allen Brown	Elizabeth Davis
Mattie Friday	Kerry Campbell	Marie-Nelsy Kouassi
James Lemaux	Charles Cofer	Patrick Taylor
Robyn Marchand	James Dodge	
Kristen Morris	Graham Livesey	
Patrick Nye		
Joseph Tischner		
Peter Winther		
Chris Yarbrough		

Welcome New Members

HGS *Bulletin* Instructions to Authors

All materials are due by the 15th of the month, 6 weeks before issue publication. Abstracts should be 500 words or less; extended abstracts up to 1000 words; articles can be any length but brevity is preferred as we have a physical page limit within our current publishing contract. All submissions are subject to editorial review and revision.

Text should be submitted by email as an attached text or Word file or on a clearly labeled CD in Word format with a hard copy printout to the Editor.

Figures, maps, diagrams, etc., should be digital files using Adobe Illustrator or Adobe Photoshop. Files should be saved and submitted in .ai, .eps, .tif or .jpg format. Send them as separate attachments via email or CD if they are larger than 5 MEGs each, accompanied by figure captions that include the file name of the desired image. DO NOT EMBED them into your text document; they must be sent as separate files from the text. DO NOT USE POWERPOINT, CLIP ART or Internet images (72-DPI resolution) as these do not have adequate resolution for the printed page and cannot be accepted. All digital files must have 300-DPI resolution or greater at the approximate size the figure will be printed.

Photographs may be digital or hard copy. Hard copies must be printed on glossy paper with the author's name, photo or figure number and caption on the back. Digital files must be submitted in .tif, .jpg or .eps format with 300-DPI or greater resolution at the printing size and be accompanied by figure captions that are linked by the file name of the image. The images should be submitted as individual email attachments (if less than 5 MB) or on CD or DVD.

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9	$800	$1,300	$2,500	$4,700						
8	$750	$1,250	$2,250	$4,300						
7	$600	$1,100	$2,200	$3,850						
6	$550	$950	$1,800	$3,500						$2,000
5	$500	$800	$1,600	$3,000	$4,700	$4,500	$4,350	$4,000		
4	$450	$650	$1,300	$2,500						
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