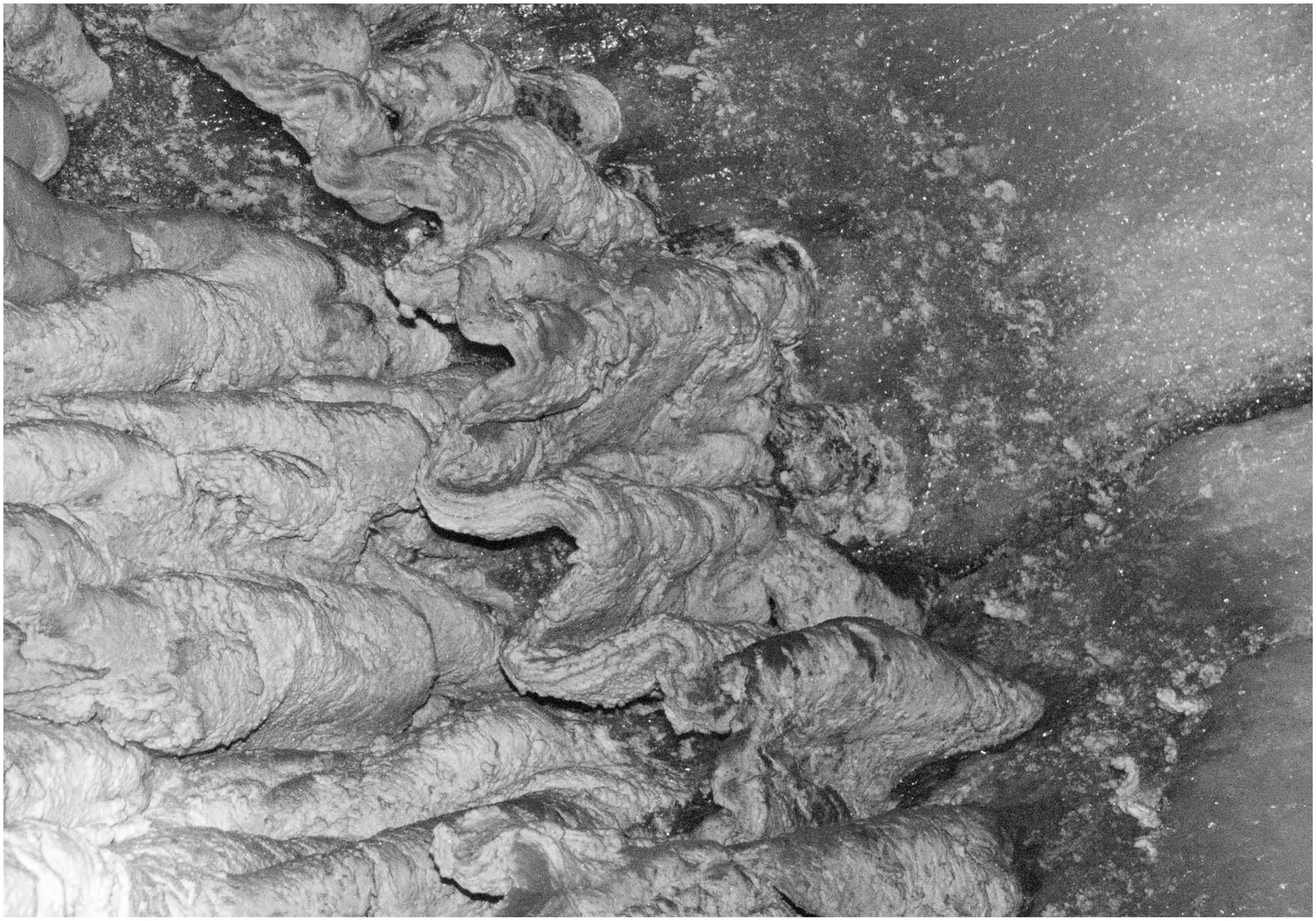

37th Annual GCSSEPM Foundation Perkins-Rosen Research Conference
December 3—6, 2019, Houston, Texas

Salt Tectonics, Associated Processes, and Exploration Potential: Revisited: 1989—2019

Editors: J. Carl Fiduk and Norman C. Rosen

Program and Abstracts

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Salt Tectonics, Associated Processes, and Exploration Potential: Revisited: 1989–2019

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Charles Davidson Hall, Noble Energy
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Edited by

J. Carl Fiduk
Norman C. Rosen

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Foreword

"It was 20 years ago today, Sgt. Pepper taught the band to play." Well no, that is not quite correct. Yet it was 30 years ago that the first conference on salt tectonics was held as the Tenth Annual GCSSEPM Foundation Research Conference. The conference held in 1989 emphasized the basics as known at the time: the rift origin of the Gulf of Mexico, the extent of autochthonous and allochthonous salt, the delineation of regional salt provinces, descriptions of salt structural styles, limited understanding of internal salt characteristics, and simple salt-sediment interactions. It was dominated by observations made in the northern Gulf of Mexico although there were papers on West Africa and the Canadian Arctic. The then chairman of the GCSSEPM Board of Trustees, Clarence Albers, suggested that "perhaps at some future time a reprise of this topic may be appropriate…." That time is now.

My initial thoughts when proposing this conference was to do exactly as Clarence Albers suggested, to reprise the topics covered in the meeting 30 years ago. However, I quickly realized that this would be wholly inadequate and fail to cover or acknowledge all the progress that has been made since that first meeting. So a balancing act was required. To cover all the progress I needed to invite the cream of those seasoned professional and scientists to present their works. But rather than just nostalgically look at the past, the conference should also eagerly focus itself on the future. To that end very deliberate attempts were made to include bright young professionals and promising graduate students in the program. A solid mix of presenting what we have learned and where we are headed is the game plan. Seven of the 33 planned speakers (21%) will be enthusiastic young professionals.

What we have learned about salt and its behavior during the last 30 years is quite an impressive step beyond our initial understandings. Most importantly, we must recognize and acknowledge that much of that understanding has come from observations and research outside the Gulf of Mexico. Yes, the Gulf of Mexico is probably the most studied basin in the world but it is not the only place to learn about salt. The first day has five talks focused on international settings including 1) the La Popa Basin, Mexico, 2) the Eastern Mediterranean, 3) the Campos Basin, Brazil, 4) the Spanish Pyrenees and Catalunya, and 5) the Northern Calcareous Alps and Pyrenees. Day 2 has eight talks focused on various salt basins around the world. In one of those papers the authors introduce a subject that would have been impossible 30 years ago: they present a methodology for producing a 3D model of the interior of a salt diaper using cores, well logs, and ground-penetrating radar. Yes, we have left the 1980s behind. The key message is that there is a lot to learn from all the world's salt basins. By opening our eyes to these other salt basins worldwide we can shorten our time on the learning curve. Every salt basin has something valuable to teach us.

This is not to say that the Gulf of Mexico is now "mature" and that we know everything there is to know about it. That is far from the truth. Although our current understanding of the northern Gulf of Mexico is light years ahead of where it was 30 years ago, the papers to be presented here highlight how much is still unknown and yet to be discovered in this basin. The age of the Louann salt is very much in question and past assumptions are being challenged. Many papers bring up this question and three papers in particular address this very topic: 1) The age of the Louann salt: Insights from historic isotopic analyses in salt stocks from the onshore interior salt basins of the northern Gulf of Mexico, 2) Tectonic models for the Gulf of Mexico in light of new Bajocian ages for proximal salt deposition, and 3) Paleo-oceanographic preconditioning promotes precipitation: how the global context is a key factor for understanding Bajocian Louann salt deposition. The timing of rift basin formation in the Triassic, and the depositional environments present within the basin is another very hot topic. How much time is missing between the top of the synrift sediments and the emplacement of salt? How long did the salt deposition phase last? Did the sea water that gave rise to the Louann salt come from the Pacific or the nascent Atlantic? These questions and more will addressed.

Conducting my part in producing this conference is something I have always aspired to do. Ever since I attended my first GCSSEPM conference back in 1989, I've felt it was a task on my "to do" list. If I had truly known how much work it was going to be when I proposed the conference topic to Tony D'Agostino in 2017, I might have had second thoughts. But now that it is done I am very happy to have made the commitment. I consider this part of my giving back to the geologic community that has given so much to me. In my 37 year career (and still going) there have been multiple ups and downs, yet the highs far overshadow the lows. This is one of my high points and I am pleased to share it with so many friends and colleagues.

My part in this reminds me that I am not alone. There are many others who have contributed to this and all the past conferences who deserve credit. To name everyone is impossible but to pay homage and respect to those giving service does not happen often enough. Most deserving is Gail Bergan. Without her "the Minnow would be lost." She makes everything concerning the conference publication and website work efficiently. You have my gratitude. I also want to pay respect to the guys driving the boat, our past GCSSEPM Foundation Directors Bob Perkins, Norm Rosen, Tony D'Agostino, and current Director John Suter. Without them there would not be a Perkins-Rosen research conference for us to attend and our science would be much poorer without it. Thank you gentlemen for your time, your service, and your willingness to give back for the benefit of everyone else. We are in your debt.

Carl Fiduk
Technical Program Chair

The GCSSEPM Foundation greatly appreciates the generosity of Noble Energy in providing the Charles Davidson Hall as the venue for the 2019 Perkins-Rosen Conference. This generosity was facilitated by Carmen M. Fraticelli, Excellence and Portfolio Manager, and Jim Demarest, Vice President of Exploration. We thank Brad White and the entire AV staff of Noble Energy for their efforts in putting on the presentations and all the other Noble employees who were involved in staging this event.

We further thank the staff of SEPM (Society for Sedimentary Geology) of Tulsa, Oklahoma, particularly Cassie Turley, Hayley Cooney and Theresa Scott, for their tireless efforts in event planning and execution. Without their help we would be unable to plan, organize, and stage an event like the Perkins-Rosen Conference.

John R. Suter, PhD
Executive Director

Salt Tectonics, Associated Processes, and Exploration Potential: Revisited: 1989–2019

37th Annual Gulf Coast Section SEPM Foundation Perkins-Rosen Research Conference

2019

Program

Tuesday, December 3

6:30–9:00 P.M. **Registration and refreshments at the BRIX Wine Cellar at Vintage Park, 110 Vintage Park Blvd. T, Houston, Texas 77070. Two drinks and appetizers will be provided per paid conference attendee.**

Wednesday, December 4

7:30 a.m. **Continuous registration (breakfast and coffee served)**

8:00 a.m. Introduction and welcome remarks: **John R. Suter**, Executive Director, GCSSEPM Foundation; **Jim Demarest**, Vice President of Exploration, Noble Energy; and **J. Carl Fiduk**, Technical Program Chair

Session 1: Lessons from the Past

Van Mount, Thomas Hearon, and Carl Fiduk, Co-Chairs

8:15 a.m. *Evolution of Marine Seismic Imaging from Late 1990s to Middle 2010s: A WesternGeco Perspective* *1*
Carl Fiduk and Kevin Lyons

8:45 a.m. *Salt-Sediment Interaction: Lessons Learned from La Popa Basin, Mexico* *2*
Katherine A. Giles, Mark G. Rowan, and Timothy F. Lawton

9:15 a.m. *It's not Just Halite—What We've Learned in 30 Years About Intrasalt Deformation* *4*
Mark G. Rowan, Janos L. Urai, J. Carl Fiduk, and Peter A. Kukla

9:45 a.m. Coffee break

10:05 a.m. *Paleogeographic Reconstruction of the Louann Salt Basin* *5*
John W. Snedden, Ian O. Norton, Michael R. Hudec, and Frank Peel

Session 2: Young Professionals Research 1

C. Evelyn Gannaway Dalton and Sian Evans, Co-Chairs

12:05—1:15 Lunch served

Session 3. Age of Louann Salt

Andy Pulham and Thierry Rives, Co-Chairs

2:45 p.m. Group discussion

3:15 p.m. Coffee break; continue group discussion

Session 4. New Ideas, Old Topics

Andy Pulham and Thierry Rives, Co-Chairs

Thursday, December 5

Session 7. Salt in Europe and Asia Minor

Maria A. Nikolinakou, Chair

11:30 a.m. *The European Zechstein Salt Giant—Trusheim and Beyond* 25
Peter A. Kukla, Janos L. Urai, Alexander Raith, Shiyuan Li, Jessica Barabasch, and Frank Strozyk

12:00—1:15 p.m. Lunch served

1:15 p.m. *3D Model of Complex Internal Structures in a Northern German Salt Diapir: A Multi-disciplinary Approach Using Drilling Cores, Well Logs, and Ground Penetrating Radar* 26
Lukas Pollok, Tatjana Thiemeyer, Marco Saßnowski, and Volker Gundelach

1:45 p.m. *Salt Tectonics and Hydrocarbon Accumulations Trapped on Diapir Flanks in the Lusitanian Basin, Portugal* 27
Ian Davison and Pedro Barreto

2:15 p.m. *Salt Tectonics Outcrops and 3D Drone Images from the Sivas Basin (Turkey) Compared to High-Resolution Seismic Lines in the GOM and B32 Angola* 28
Jean-Claude Ringenbach, Charlie Kergaravat, Charlotte Ribes, Alexandre Pichat, Etienne Legeay, and Jean-Paul Callot

2:45 p.m. Group discussion

3:15 p.m. Coffee break, continue discussion

Session 8. Advances in Modeling

Maria A. Nikolinakou, Chair

3:35 p.m. *Salt Tectonics Restoration in Basin and Petroleum System Modeling: Contribution of Physical Analogue Models and Methodologies* 29
Sylvie Schueller, Marie Callies, Jean-Marie Mengus, Nadine Ellouz-Zimmermann, and Jean-Luc Rudkiewicz

4:05 p.m. *Loading Complex Salt Isopachs: Progradation Across Segmented Salt-Filled Rift Systems* 30
Tim P. Dooley and Michael R. Hudec

4:35 p.m. *Geomechanical Modeling of Diapirism in Extensional Settings: Controls on Styles of Diapir Rise and Fall* 31
Maria A. Nikolinakou, Mahdi Heidari, Michael R. Hudec, and Peter B. Flemings

5:05 p.m. End of Day 2

Friday, December 6

7:30 a.m. **Continuous registration (breakfast and coffee served)**

Session 9. New Insights from the Northern Gulf of Mexico

Van Mount, Thomas Hearon, and Carl Fiduk, Co-Chairs

11:50—12:00 p.m. Group discussion. Meeting wrapup and adjourn.

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Cover Image

The cover image chosen for this year's conference is from Kukla et al. "The European Zechstein Salt Giant—Trusheim and Beyond": Figure 7: Cylindrical folds of anhydrite layers in rock salt, exposed by solution mining.

Evolution of Marine Seismic Imaging from Late 1990s to Middle 2010s: A WesternGeco Perspective

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Abstract

The time period from the early 1990s through to the early 2010s saw a consistent and steady increase in the (1) depth of data imaged, (2) level of seismic detail revealed, and (3) complexity of tectonic and salt structures resolved. To achieve this remarkable increase in data quality, the seismic industry made parallel advances in seismic acquisition techniques, data processing algorithms, and computer processing speed. The resulting high quality imagery has allowed interpreters, modelers, and research scientists to advance the science of salt tectonics from a relatively basic level in the early 1990s to a robust and highly integrated science in 2019.

State-of-the-art marine seismic data acquisition in 1990 involved a single vessel towing a single cable 4 km long collecting time data in a 1-2 km spaced 2-D grid. By the early 1990s, narrow azimuth 3-D time acquisition evolved. Initially this started with a single vessel towing two streamers of 4 km length and recording 8 second records. It grew to involve multiple vessels towing 3-6 streamers of 6 km length and recording 14 second records. Kirchhoff was standard advancing from post-stack time to pre-stack time migration.

In the early 2000s, time processing and depth processing existed side by side, but exploration needs were pushing for better depth data. Kirchhoff pre-stack depth volume quality was replaced by Wave Equation pre-stack depth data in areas of greater structural complexity. Depth processing now included one or two top salt-base salt pairs to image the subsalt stratigraphy.

By the mid-2000s, wide-azimuth acquisition was the procedure of choice. Vessels were towing 8-10 streamers of 7-8 km in length. Maximum offsets were reaching 8-9 km and receiver location systems were being employed. Velocity analysis employed multi-azimuth sediment tomography incorporating seismic anisotropy and later vertical transverse isotropy.

Around 2009-2010, reverse time migration became the processing algorithm of choice. Velocity fields were calibrated to subsalt well ties. Velocity analysis incorporated full waveform inversion with vertical transverse isotropy and then tilted transverse isotropy. Running multiple iterations of intrasalt and subsalt full waveform inversion would become standard practice.

In the early 2010s, WesternGeco introduced full azimuth and multi-vessel full azimuth acquisition. Proper acquisition and processing of full azimuth data required streamer steering capabilities, precise receiver positioning, advanced noise attenuation algorithms, and state-of-the-art computing facilities. Full azimuth acquisition produced maximum offsets of 14-16 km. Eventually, full azimuth and wide-azimuth data sets were merged to reduce noise and maximize the efficiency of tried and tested wide-azimuth processing routines. Seismic examples over the same location shot from 1990s to 2015 illustrate the incremental gains made in imaging the subsurface in response to these technical advances.

Salt-Sediment Interaction: Lessons Learned from La Popa Basin, Mexico

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Abstract

The state-of the-art in our understanding of salt-sediment interaction in 1989 was that stratal packages generally thin and turn-up near salt stocks/walls. This was attributed to late penetration of prediapiric strata by buoyant salt and consequent shear and structural thinning of flanking strata. The primary sources of information at that time were vintage seismic data and borehole data; i.e., poor images and one-dimensional samples of the diapir edges and adjacent sediment. This is where, starting in the mid-1990's, studies of the exceptional outcrops of La Popa basin, Mexico, provided the first systematic and detailed documentation of near-diapir sedimentologic, stratigraphic, structural, and petroleum system architecture at several different types of steep-sided salt structures including flaring salt stocks and a secondary salt weld.

The first breakthrough from analysis of La Popa outcrops was that not only do strata thin and upturn as they approach the diapirs, but they form local, angular unconformity-bound stratal packages (halokinetic sequences) that record the interplay between rates of passive diapiric rise and local sediment accumulation. Moreover, structural analysis revealed that the thinning was depositional rather than structural and that the upturn was caused by drape folding of roof strata during passive diapirism instead of drag folding.

Sedimentologic studies of halokinetic sequences developed in various depositional systems, ranging from nonmarine (mostly fluvial) to relatively sediment-starved outer-shelf systems in both siliciclastic and carbonate rocks, showed that the diapirs had variable topographic relief. Higher relief was created during periods of relatively slow sedimentation, whereby diapir-rise rate outpaced sediment accumulation. This scenario resulted in deflection of clastics away from the high, intercalation of mass-wasting deposits derived from failure of the diapir roof, and the diapir itself, as well as generation of an elevated substrate in a regionally deeper water, siliciclastic-starved setting that permitted prolific carbonate reef growth over the diapir high. Conversely, when sediment accumulation rates exceeded diapir rise, relief was minor to nonexistent and sediment deposition was controlled more by regional processes. The cyclic variations in sediment-accumulation rates vs diapir-rise rates in halokinetic sequences were subsequently shown to stack into higher order composite halokinetic sequences, which were correlated to regional depositional sequences and relative sea-level changes. Composite halokinetic sequences form two end-member types that vary in drape-fold geometry and scale, which is ultimately related to the thickness of the roof panel being drape folded during diapir rise.

The La Popa outcrops also led to the first detailed structural analysis of a secondary weld formed by squeezing of a salt wall and the lateral variation in associated small-scale structures over its 24 km length. There is little to no deformation of flanking strata on the northwest portion where it is still an apparent weld (>50 m of remnant evaporite). Where it is a discontinuous weld (with pods of gypsum up to 30 m wide), there is increased fracture density up to 15 m into the adjacent strata. The southeast 8 km of the structure is a complete weld with a damage zone up to 50 m thick in the down-dropped siliciclastics due to post-welding weld-parallel strike-slip deformation.

Similar sedimentologic, stratigraphic, and structural styles/trends have subsequently been documented in many other outcropping salt basins worldwide (e.g., Paradox Basin, Nova Scotia, Spanish Pyrenees, Atlas

Mts., Zagros Mts., Flinders Ranges) and in subsurface equivalents. Ongoing studies that build on the fundamental relationships documented in La Popa basin include but are not limited to: changes in stratal and structural style along strike or around diapirs, depositional response to halokinesis of deep water sedimentary systems, sediment routing systems in salt basins, as well as the relationship of minibasin-wide growth strata to halokinetic sequences.

It's not Just Halite—What We've Learned in 30 Years About Intrasalt Deformation

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Abstract

Thirty years ago, salt bodies were generally depicted on cross sections or seismic interpretations with just outlines or solid colors. Exceptions were made by those working in salt mines or drilling through salt in basins such as the southern Permian basin of Europe. Over the past three decades, increased penetrations of salt layers and vastly improved seismic images have forced a reevaluation of how we think of diapirs and other salt bodies.

Salt layers are in reality layered evaporite sequences comprising interbedded incompetent layers (halite and bittern salts) and competent layers (anhydrite, carbonates, and siliciclastics). This results in a pronounced rheological stratification, with both frictional and ductile materials and a wide range of effective strength. Ductile flow of halite, as the dominant mineral, is understood reasonably well, but much less attention has been paid to the stronger layers, whose behavior depends on the predominant mode of deformation.

In layer-parallel extension, boudinage of competent layers is easy and forms ruptured stringers within a halite matrix. In layer-parallel shortening, competent layers are stronger, and tend to maintain coherency in multilayer buckle folding. In differential loading, extension and the resultant stringers dominate beneath suprasalt depocenters while folded competent beds characterize salt pillows. Finally, in tall passive diapirs, stringers generated by intrasalt extension are rotated to near vertical and form tectonic melanges during upward flow of salt. In all cases, strong layers are progressively removed from areas of salt thinning and become increasingly disrupted in other areas as deformation intensifies.

The varying style of intrasalt deformation impacts seismic imaging and analyses of both seismic and well data. Both may be interpreted to suggest that diapirs and other areas of more intense intrasalt deformation are more halite rich than is actually the case.

Paleogeographic Reconstruction of the Louann Salt Basin

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Abstract

The presence of Jurassic age salt in the Gulf of Mexico has been known for almost 60 years, originally recognized as two separate salt bodies. Reconstruction of the original saline basin as it appeared prior to sea floor spreading has been difficult to carry out due to subsequent allochthonous salt movement that obscures stratal relationships at depth. However, a new approach to seismic mapping of the Louann salt using its tectonostratigraphic character allows recognition of distinct Louann facies transitions from deep basin to onshore lapouts. Halite-dominated Louann is more ductile, often seismically dim, and readily facilitates fault detachment. Halite likely formed in the deep basin, with coeval anhydrite forming in shallow water sabhkas and evaporitic lagoons. Anhydrite-dominated sections are seismically and structurally distinct having high amplitude/continuity and a less ductile character. A zone of mixed seismic response that we infer to be interbedded halite and anhydrite separates these seismic facies (Fig. 1; Snedden and Galloway, in press).

Our new paleogeographic reconstruction of the Louann salt has been developed on the basis of this seismic facies mapping, in combination with new plate tectonic models. 87/86Sr ratios from interior salt basins indicate a proxy age of 170-ma when matched against the global strontium seawater curve (Fig. 2; Snedden and Galloway, in press). Although a 170-ma age for the Louann salt is 7-8 ma earlier than previous estimates (Hudec et al. 2013), this occurs during a phase when various plates are in closer proximity and thus conditions are more conducive to restriction and evaporation.

This reconstruction also allows evaluation of two contrasting hypotheses regarding source of the original seawater that fed this saline giant in the deep Gulf of Mexico basin. Our restoration shows narrow gateways to the Atlantic Ocean, from the deep Louann basin through the Florida straits, Northern Cuba and the Bahamas. The chain of narrow basins connecting the Atlantic to the Gulf may have acted to deplete incoming seawater of all but Na and CL, evidenced by the remarkably pure Louann halite in the deep basin (Peel, this volume). The mapped configuration of narrow passages in the eastern Gulf of Mexico and dominance of basin marginal anhydrite in Mexico (versus halite elsewhere) also leads one to question the conventional model of a marine connection between the Louann basin and the Pacific Ocean. Pacific affinity macrofauna, originally a critical data point supporting the Pacific seawater entry model, are now known to be younger than the Louann salt.

Salt is a critical component of the prolific Gulf of Mexico petroleum system, setting up traps, providing top seal, and mitigating heat flow so that Mesozoic source rocks generate later in the basin burial history. Understanding the original distribution of Louann salt is also essential to basin modeling and structural restorations.

Intrasalt Structure and Strain Partitioning in Layered Evaporites: Insights from the Messinian Salt in the Eastern Mediterranean

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Abstract

Determining the composition and internal structure of salt bodies is important for safe drilling through thick salt sequences and enables us to build better velocity models that allow more accurate seismic imaging of near-salt geology. However, due to typically poor seismic imaging within salt bodies, and a lack of outcrop and well data, the nature of the lithological control on intrasalt deformation is still poorly understood.

The Messinian evaporites are lithologically heterogeneous, shallowly buried, and only weakly deformed along the Levant Margin in the eastern Mediterranean. The halite-dominated units are interbedded with other evaporitic minerals (e.g., anhydrite, gypsum, potash salts) in addition to clastic units. This lithological heterogeneity leads to rheological heterogeneity, and the different mechanical properties of the various rock types control strain partitioning within the deforming salt sheet.

A large, high resolution 3D seismic reflection data set provides us with an opportunity to assess how intrasalt strain varies within thick salt (up to 2 km) during the early phase of evaporite deformation. We calculate strain on individual reflectors and show that strain varies laterally and vertically across the contractional domain of the Levantine Basin. These results provide insights into how seismically derived strain profiles may reflect the rheological properties of the deforming units and changes in the kinematic evolution of the salt sheet through time.

Salt Tectonics Within Strike-Slip Systems, Campos Basin, Brazil

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Abstract

The Campos basin is a well-studied, economically important basin located in the southeastern Brazilian coastal margin. Salt tectonics play an integral part in the basin's development by deforming the overlying postsalt sedimentary package and forming a variety of extensional and contractional structures. The majority of the salt structures within the basin are oriented perpendicular to the evaporite flow direction, which radiates seaward from the continental shelf break. As such, the basin is structurally similar to most other salt-bearing Atlantic passive margin basins. However, the north-central portion of the basin is marked by several peculiar structural elements, such as the presence of northwest trending lineaments and faults near the Roncador and Frade oil fields.

This portion of the basin contains reactivated basement faults that, together with salt tectonics, have formed important controls for the structural and stratigraphic features found in the deep-water. These local reactivations have (re)deformed the earlier salt structures previously formed by gravitational gliding and created a disparity with the previously defined passive margin setting.

2D and 3D seismic data integrated with well control covering the northern Campos basin were interpreted in order to characterize Late Aptian salt structures and were used to investigate the structural controls involved in their development focusing on the Maastrichtian-Aptian interval. Analysis of the interpreted 3D seismic showed that the salt-sediment relationship was further affected in some areas by strike-slip systems and associated basement reactivations.

Salt structures within the study area are associated with basement highs and have been (re) oriented into west-northwest/east-southeast alignments, which is parallel to sub-parallel with the original evaporite flow direction. Structures include a dextral strike-slip rhombic graben at the Albian level and a still-active strike-slip fault system which forms a large horst that limits a salt body within its normal faults. Development of the northwest and east-west trending shear zones and reactivation of north-northwest/south-southeast extensional basement-involved faults act to control the geometry of the salt structures. The presence of these strike-slip fault systems and their effect on salt tectonics has not been thoroughly characterized previously. The recognition of these features may impact the interpretation of similar features in other parts of the Campos basin and elsewhere.

Evolution of Megaflaps, Extensional-Rollover Subbasins, and Salt-Withdrawal Minibasins at Aulet and Adons Diapirs in the Spanish Pyrenees, Catalunya

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Abstract

The Aulet and Adons diapirs in the south-central Pyrenees have been variously interpreted as salt rollers or passive diapirs derived from Triassic Keuper evaporites. They are flanked by upper Albian to Turonian strata in three domains (Sopeira, Faiada, Sant Gervàs) correspondingly interpreted as extensional rollover subbasins or salt withdrawal minibasins. Pyrenean shortening resulted in contractional megaflaps in the Sopeira and Sant Gervàs domains, but the alternative salt structures and domain origins have significant implications on interpretations of subsurface geometries. We use sedimentologic and stratigraphic analysis to resolve if the Aulet and Adons diapirs evolved as salt rollers or passive diapirs, followed by structural analysis to interpret the kinematics of megaflap rotation during the Pyrenean Orogeny.

The Sopeira domain, south of the Aulet diapir, contains subvertical Aulet Fm. preserving an expanded carbonate ramp shoreface succession showing broad facies and thickness changes in the lower Aulet Fm., minimal variations in the upper Aulet Fm. except isolated slump blocks, and no evidence of passive diapirism. This suggests the Sopeira domain evolved as an extensional-rollover subbasin bound by the Aulet salt roller to the north and a buried salt roller to the south. The Sant Gervàs domain, south of the Adons diapir, contains completely overturned Santa Fe, Pardina, and Agua Salenz strata. The subsurface geometry is uncertain, but an extensional-rollover origin, bound to the north by the Adons salt roller and to the south by a buried salt roller, best explains the salt-sediment relationship and most realistically allows for later rotation to completely overturned. The Llastarri fault zone, interpreted as a buried salt ridge, was first part of the lateral margin of the older Sopeira basin, sourcing slump blocks, and later was the lateral footwall of the younger San Gervàs basin. The Faiada domain, west of the Adons diapir, comprises an anomalously expanded Santa Fe, Pardina, and Agua Salenz succession with diapir-derived detritus and halokinetic sequences, indicating at least some salt evacuation adjacent to a passive interface of the Adons diapir. Structural analysis highlights the impact of inherited extensional vs. passive salt structures on Pyrenean shortening and megaflap rotation.

The Age of the Louann Salt; Insights from Historic Isotopic Analyses in Salt Stocks from the Onshore Interior Salt Basins of the Northern Gulf of Mexico

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Abstract

The Louann Salt is an evaporitic succession deposited in the Gulf of Mexico during the latter stages of Mesozoic-age crustal stretching and likely immediately prior to oceanic spreading in the basin. The importance of the Louann cannot be overstated, particularly to the petroleum systems of the Gulf of Mexico. Since its precipitation, the original Louann has been on the move, leaving autochthonous remnants and resulting in a myriad of allochthonous and para-autochthonous intrusive diapirs, stocks, sheets, canopies, wings, etc. At a reservoir scale, and there are numerous Gulf of Mexico productive units throughout the Mesozoic and Cenozoic, the age of the Louann can be regarded as somewhat academic. At a regional and basin scale the tectonostratigraphic architectures revealed by remote sensing techniques (seismic reflection, gravity, and magnetic surveys, etc.) are poorly constrained by absolute ages at the level of the Louann and the continental-dominated stratigraphy that predates and immediately post-dates the evaporites.

Since the late 1980s, the Louann salt has been interpreted as Middle Jurassic-Callovian in age, not exclusively but this is the default interpretation in most publications that refer to the Louann. This age dating approach has been called "stageology" by a respected colleague and is a well-established practice of convenience when absolute age is uncertain. The assigned age of Callovian for the Louann may well be correct. In the spirit and theme of this meeting we revisit the age of the Louann salt and explore an alternate age interpretation.

The study presented here was part of an investigation undertaken originally by Cobalt International Energy and Total E&P Americas, and continued by Total, that sought to constrain the timing of Jurassic events in the offshore Eastern Gulf of Mexico (EGoM). Biostratigraphic data from wells encountering marine Jurassic in the offshore EGoM provide some indication that post-Louann stratigraphy is as old as Callovian, albeit with uncertainties. Also, in the EGoM is a seismically mapped succession above the Louann that is up to 8,000 feet in thickness, named the Sakarn series in this volume. This succession has not been encountered by the numerous wells that penetrate autochthonous or quasi-autochthonous salt in the onshore interior salt basins of the Northern Gulf of Mexico but implies

additional time post-Louann and prior to the onshore and offshore aeolian-fluvial deposits of the Norphlet Formation. The question being asked in our exploration team in 2015 was; "Does the Callovian have the temporal capacity; 2.6 Ma, to contain the entire Louann and the Sakarn series, and perhaps also including the increasingly economically important Norphlet Formation?"

Our investigations lead to US Atomic Energy Agency (AEA) and US Department of the Interior projects that, in part, extensively drilled and cored Louann salt diapirs across the onshore Northern Gulf of Mexico during the post-WWII period and up to the early 1960s. These AEA projects were concluded by the end of the 1980s; soon after, organic and inorganic analyses of the extensive US Government Louann cores started to appear in peer reviewed journals. Within these geochemical data are isotopic analyses including $^{87}Sr/^{86}Sr$ results from deep within the salt stocks of Louann diapirs. In the intervening two to three decades, the Phanerozoic record of $^{87}Sr/^{86}Sr$ values in the world's ocean has been refined and a robust record now exists for the Jurassic.

Comparison of the $^{87}Sr/^{86}Sr$ data derived from AEA Louann core samples against the $^{87}Sr/^{86}Sr$ record for the Jurassic provide an intriguing option for interpretation of the Louann age. We propose that an age window of early Bajocian through early Callovian; ~170 Ma to ~165 Ma, 5 m.y. of duration, should be considered for the age of the Louann and for the 6,000 ft of post-Louann sediments in the EGoM. This time window is far from certain. New isotopic data may well refine a time window greater or shorter than we suggest. Establishing a robust age for the Louann will help in refining tectonostratigraphic models for the early history of the Gulf of Mexico Basin. Existing isotopic analyses offer a guide and new isotopic analyses may deliver a solution.

Middle Jurassic Tectonic Models for the Gulf of Mexico in Light of New Bajocian Ages for Proximal Margin Salt Deposition

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Abstract

Recent Bajocian Sr87/86 ages (169 Ma) for Louann, Campeche, and other evaporite samples in the northern, southern, and western proximal rims of the Gulf of Mexico Basin (GoM) suggest that new perspectives on the basin's rift and drift history are warranted. Presently, sea-floor spreading is believed to have started in the Oxfordian because (1) salt is usually considered Callovian-early Oxfordian and the basinward limits of Louann and Campeche salt, having been separated by spreading, closely match the limits of the intervening oceanic crust; and (2) Yucatán and the reconstructed, little-faulted, base-salt unconformity along GoM margins can be accommodated neatly into current early Oxfordian (~160 Ma) North America-South America tectonic reconstructions. However, reconstructions for Bajocian time (~169 Ma) generally do not accommodate the great area of this nearly planar unconformity. Three possible explanations are evaluated here: (1) that Bajocian North America-South America reconstructions are too tight; (2) that salt deposition began in the Bajocian but persisted through Bathonian–early Oxfordian time before spreading and hence offlapped from the dated locations along the proximal GoM margins; and (3) that all salt is Bajocian, but that it flowed basinward to the eventual line of initial Oxfordian spreading. We assess explanation 1 by a sensitivity analysis of the Equatorial Atlantic component of the circum-Atlantic reconstruction, concluding this option is viable. If correct, explanation 1 implies a Bathonian rather than an Oxfordian onset of seafloor spreading, along with several other important aspects of GoM evolution. Explanations 2 and 3 imply ongoing Bathonian-early Oxfordian basement expansion which is not readily identifiable in seismic data, but which might be allowable if the base-salt surface beneath the Sigsbee slope is eventually shown to be non-planar and if salt deposition is shown to be younger in the eastern GoM than in the western/central GoM. These options will thus remain viable unless Sr isotope ages for distal salt eventually prove to be Bajocian, as in the proximal margins. We find explanation 3 least likely because littoral-neritic paleo-environmental assignments for Upper Jurassic strata in certain offshore wells suggest maintenance of shallow water conditions above salt far into the offshore and hence only minor salt deflation by that time. The new ages suggest that the Huayacocotla area of central, continental Mexico is the most likely link to the world ocean in Bajocian time because Bajocian-Bathonian Huehuetepec and equivalent evaporites occur there. Further, we highlight and suggest alternatives for resolving a longstanding conundrum posed by the thin salt package lying upon the little-faulted, postrift, base-salt unconformity in the eastern GoM that lies at the same structural level as the oceanic crust. We suggest that deep-water salt deposition may provide a viable alternative explanation to outer marginal collapse at the rift-drift transition. Finally, we present a 195 Ma (Early Jurassic) reconstruction using the looser Equatorial Atlantic fit which shows that the looser fit accords well with reconstructions of western Pangea.

Paleo-Oceanographic Preconditioning Promotes Precipitation: How the Global Context is a Key Factor for Understanding Bajocian Louann Salt Deposition

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Abstract

The Louann Salt of the Gulf of Mexico (GoM) is strikingly different from most other halite giants; unstratified and with no Usiglio sequences; it consists mostly of halite intimately mixed with anhydrite. The measured $CaSO_4$ content is lower than that of normal seawater. An evaporite unit deposited by full evaporation of seawater of normal composition (Babel and Schreiber, table 1, 2014) should contain ca. 4% by weight $CaSO_4$ (anhydrite plus gypsum recalculated as $CaSO_4$). This is consistent with experimental evaporation; the classic data of Usiglio (1849) gives 4.4% by weight $CaSO_4$ (Dean, 1987). However, compositional measurements of the Louann indicate a significantly lower value. Figure 1 compares the predicted weight fraction of $CaSO_4$ with observed composition of Gulf of Mexico salt bodies based on data from individual wells and mines (Martinez et al., 1979; Dix and Jackson, 1981; Land et al., 1988; Fredrich et al., 2007). Dissolution by groundwater flow around shallow diapirs results in concentration of less soluble components, as shown in Figure 2A, (Kyle and Posey, 1991; McManus and Hanor, 1993), but the geometry of deep-water salt sheets is less favorable to large scale dissolution (Figure 2B) and the observed mean wt% $CaSO_4$ for deep-water salt sheets (2.03%) is probably closer to that of the original Louann. Thus the Louann is significantly deficient in $CaSO_4$; this composition cannot simply be achieved by evaporation of raw seawater. The simplest explanation for the observed sulphate deficiency is that the water from which the Louann was deposited had already been pre-processed on its journey through a chain of basins before it reached the Gulf of Mexico; i.e., the missing sulphate exists, but it was deposited in another basin.

Hitherto, the Gulf of Mexico basin has been seen in a relatively local context, initially with a restricted connection to normal oceanic water, either eastwards into the Tethys ocean via the North Atlantic (e.g., Pindell and Kennan, 2001), or westwards into the Pacific (Berggren and Hollister, 1977; Salvador, 1991). The Louann has conventionally been thought to be of early Callovian age, but 87Sr/86Sr strontium isotope data indicates that the Louann is older, deposited at ca. 170 Ma (early Bajocian), (Pulham, 2016 pers. com.; Pulham, et al., 2019). Assigning an older (Bajocian) age to the onset of salt deposition changes the balance of evidence towards an easterly water source. Ammonite provinces described by Callomon (2003) demonstrate that, throughout the Middle Jurassic, the basin chain was linked eastwards to the Tethyan Ocean, and at times northwards to the Boreal Sea, but a fully open westwards connection to Pacific fauna did not come into existence until the Late Jurassic. As shown by Scotese (2013), the mid-Jurassic Gulf of Mexico is better viewed as a Tethyan rather than an Atlantic basin,

The global plate tectonic context of the Gulf of Mexico at 170 Ma (Fig. 3) shows that the Louann was deposited in a rather special plate setting related to the initial breakup of Pangea (Veevers, 2004); it lies at the western end of a chain of newly opening basins in the middle of a supercontinent. Breakup occurred as Gondwana and Laurasia progressively "unzipped" westwards, so that basins in the east opened earlier and at any given time tended to be wider than those in the west. Major rift regions and early ocean basins, within which water could circulate, were separated by strike-slip dominated zones which formed choke points, restricting ocean circulation between the basins. Figure 4 shows the paleogeography of one such choke, con-

necting the Tethys and the Central Atlantic (adapted from Sibuet et al., 2012). Plate reconstructions indicate that the gap between continental basement blocks was narrow, but a full paleo-oceanographic reconstruction must also incorporate the effects of sediment deposition. In this region, deposition of platform carbonates in the southern straits and deposition of marine mud and clastic sediments in the northern straits has the effect of making the marine connection narrower and shallower. Water flowing from the Tethys into the Central Atlantic did so by an extremely restricted and shallow connection, and it can only have involved the shallowest part of the water column.

Figure 5 shows the connection between the Louann Sea (the water body occupying the early Gulf of Mexico at the time of salt deposition) and the proto-Caribbean, based on detailed 2D seismic mapping on a 5-10km grid spacing by the author and Magdalena Curry. This reveals a well-defined channel system feeding the Louann Sea, which was 500km long, tortuous, and in places both narrow and shallow. The author suggests that flow through this system is likely to have been one-way with no return flow component.

The climate within the middle of the fragmenting Pangea supercontinent was hostile. The entire chain of basins lay within the low humidity arid tropic zone, within the center of a supercontinent; its western part was flanked by sand deserts (San Rafael Group), and average summer temperatures probably exceeded 100ºF (Harris et al., 2017). Conditions were ideal for rapid water evaporation; climate modeling (Chandler et al.,1992) indicates that water loss by evaporation exceeded gain by precipitation across the entire western Tethys, resulting in net evaporation in excess of 2m/yr in the region of the Louann basin. However, salinity enhancement by evaporation was countered by the flushing effects of strong marine currents passing through the basin chain (Figure 6A). Of these, the most significant was the Viking current, which effectively flushed the entire eastern half of the basin chain (Korte et al., 2015). At the start of the Aalenian, mantle uplift raised the North Sea region, blocking the Viking current (Underhill and Partington, 1993), turning the basin chain into a dead-end street and allowing potential salinity buildup. The onset of salt deposition appears to have been delayed by a regional climatic cooling event, as temperatures dropped by 15°C in the early Aalenian (Korte et al. 2015). At the start of the Bajocian, this cold period ended (Suchéras-Marx, 2013), as δ18O measurements in oyster and belemnites show that Tethyan water grew significantly warmer (Dera et al., 2011). Climatic and paleo-oceanographic conditions were now perfectly set up for westwards-increasing brine concentration throughout the chain. The author suggests that concentration to the point of gypsum/anhydrite precipitation was reached in the area of the proto-Caribbean, so that the brine passing onwards into the Louann basin was both highly concentrated in NaCl and partially depleted in $CaSO_4$. This enabled very rapid precipitation of the Louann salt giant and explains the observed sulphate deficiency.

Synthesizing Old Questions with New Developments in Caprock Research: Is it Time to Abandon Well-Trodden Paths?

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Abstract

In 1901, the Lucas Gusher at Spindletop salt dome marked the beginning of the Texas oil boom in the USA. The reservoir rock at Spindletop is carbonate caprock. Originally identified as dolomitic caprock, it not only yielded oil, but also large quantities of native sulfur. However, more than a century later, major gaps remain in the understanding of how caprocks form.

Caprocks are found at the top of salt diapirs when dissolution of readily soluble halite (NaCl) leads to the accumulation of less soluble calcium sulfate minerals, such as anhydrite ($CaSO_4$) and gypsum ($CaSO_4 \cdot 2H_2O$), as well as other insoluble constituents. When the sulfate minerals come into contact with oil or gas, the sulfate is thermochemically or microbiologi-

cally reduced to sulfide and the oil or gas are oxidized to carbonate, driving the transformation of anhydrite and gypsum into limestone ($CaCO_3$) along with the production of sulfide and/or native sulfur. Caprocks remain on top of the salt diapir or are rotated off into a flanking/lateral position. They may serve as reservoirs, traps, seals, or conduits for oil or gas but may also pose drilling hazards. Interestingly, in the Gulf of Mexico, with the exception of near-coastal sites, caprock is often considered to be absent at most offshore salt domes, but it is present at Challenger Knoll at a water depth of 3700 m in the center of the Gulf.

Over the last decade, the salt-sediment interaction research consortium at The University of Texas at El Paso has made a number of discoveries that may reshape the understanding of caprock formation. These include:

There are a much wider variety of caprock fabrics than previously reported.

The geochemistry of Gulf Coast salt diapir caprocks indicates heat-loving microbes (thermophiles) generate native sulfur from sulfate without requiring molecular oxygen, challenging the paradigm that molecular oxygen is critical for the genesis of large native sulfur deposits.

Steeply dipping carbonate lithologies found between diapirs and adjacent strata can represent rotated diapir-flanking caprock but can also correspond to upturned older strata or carbonates formed in a basin next to an exposed diapir.

Petrographic-geochemical studies of caprock from the Gypsum Valley salt wall in Colorado indicate that dolomite ($MgCa(CO_3)_2$) is an early carbonate phase, generating the conundrum of how replacement of calcium sulfate minerals can result in the formation of a carbonate rock with high magnesium content.

These surprising insights exemplify that much remains to be learned about caprock formation and that carbonate and sulfur minerals may serve as untapped archives of the history of fluid flow and hydrocarbon migration in settings with active salt tectonics.

Minibasins Involved in Fold and Thrust Belts: From Their Development in Passive Margins to Contractional Reactivation (Examples from the Northern Calcareous Alps, Pyrenees and Experimental Modeling)

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Abstract

It is well known that the presence of salt horizons and salt structures have a strong influence on the structural style of fold-and-thrust belts. They also affect the inversion of rift basins that form during lithospheric stretching preceding thermal subsidence and passive margin development. However, minibasins and salt structures that form after rifting ceases have only recently been recognized in orogenic systems such as the Northern Calcareous Alps or the Pyrenees. We aim to characterize the structure of inverted minibasins but the challenge is to understand, and match, the present-day contractional structure with a reasonable preorogenic configuration. Yet, we still lack a proper understanding on the development of these salt-sediment systems and particularly, how salt tectonics is triggered and evolves through space and time. Two fundamental triggering mechanisms of passive margin salt tectonics are known: (1) extension, by gravitational collapse and gliding, and (2) differential loading. A key question is: do these mechanisms occur at the same time or does one commonly follow the other? In the latter case, which one is first? Which one dominates? Does it depend on the location and timing of deformation on the passive margin?

In this contribution, we provide several case studies from the Pyrenees and the Northern Calcareous Alps (Austria), both examples of fold-and-thrust belts that have deformed passive margins involving salt-basins. We investigate these contractional systems by geological mapping, cross-section construction, and structural restorations. Uncertainties are reduced by (1) integrating subsurface data if available, (2) by means of experimental modeling studies, and (3) by comparison to present day continental margins.

The Pyrenees involved the North-Iberian passive margin where salt tectonics was triggered by extension during Late Jurassic-Early Cretaceous rifting. It continued during the subsequent early Late Cretaceous thermal phase preceding the onset of contraction. Salt structure location was fundamentally controlled by the distribution (and redistribution) of the Triassic salt. Extensional collapse occurred at the edge of salt inflated areas, mainly at the footwall of the main rift-margin extensional faults, and preferentially in the relay zones of the segmented Pyrenean rift system. Basinward, halokinetic geometries reveal that salt-withdrawal minibasins also occur, these depocenters shifted from those of the previous rift basins.

Recent field work and analysis of existing data from the Northern Calcareous Alps fold-and-thrust belt of Austria has shown characteristic structural styles related to salt tectonics: (A) multiple structural orientations for folds and faults, (B) strong changes in fold plunges, (C) large panels of fully overturned stratigraphy (e.g., such as megaflaps), (D) mechanical contacts omitting or repeating stratigraphy (i.e., apparent extensional faults passing laterally into reverse/thrust faults), and (E) stripes of severely deformed evaporites or their equivalent leached remnants (i.e., salt welds, thrust welds) that bound thrust units having markedly differ-

ent sizes and contrasting stratigraphic thicknesses. These features point out the reactivation of structures involving Permian salt. Similar to the Pyrenees, extensional collapse of the late rift to post-rift sequences occurred at the edge of a salt basin. Basinward, minibasins characterized by highly subsiding carbonate platforms formed by salt evacuation of inflated areas, with carbonate aggradation at rates larger than those provided by thermal subsidence alone (~2 km/m.y.).

In both contractional systems (i.e., the Pyrenees and the Northern Calcareous Alps), Alpine orogenic shortening has completely sheared off the sedimentary cover from its original presalt rifted basement; hence, the relationships between salt structures, with those structures responsible for crustal thinning have been largely obscured. The present structure of the minibasins in the Pyrenees and the Alps is characterized by large panels of vertical to significantly overturned sediments. At some places, overturned panels involve a relatively reduced succession away from the minibasin depocenters and have been interpreted as the result of contractional deformation in sediments overlying the salt inflated areas. However, a problem lies in the interpretation of vertical to overturned panels (megaflaps) involving the depocenters of the minibasins. Experimental models show a moderate amount of rotation during the contractional deformation of salt-withdrawal minibasins. This emphasizes that inversion of salt rollers and minibasins developed by extensional collapse, and probably above a stepped base salt topography, better explain the presence of such large and thick overturned megaflaps. Field evidence from the Alps and the Pyrenees also suggest that components of passive margin thin-skinned extension and downbuilding better explain the current contractional structure of these salt-influenced fold-and-thrust belts.

Applications of Biostratigraphy to Salt Tectonics, Northern Gulf of Mexico

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Abstract

Biostratigraphy provides rock-based interpretations of the age and depositional setting of strata which can be used to constrain structural and stratigraphic reconstructions of salt-deformed terranes. Data from seven wells drilled in the deep-water northern Gulf of Mexico are used to demonstrate the use of biostratigraphic data in differentiating suprasalt minibasins from condensed carapace sections, identifying salt welds, providing age control for salt inclusions, and providing evidence for subsalt rubble zones and overturned sections. In particular, the use of planktic microfossil and agglutinated benthic foraminifer abundances and rock accumulation rate curves are especially useful in determining the depositional setting for out-of-place sections.

On Elevators and Bulldozers: What has Changed in Salt Tectonics? Examples from Passive Margin Salt Basins

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Abstract

Salt tectonic studies emerged with the mining of salt stocks and early hydrocarbon exploration predominantly in the Paleozoic salt basins of Europe (Trusheim, 1960; Jackson 1995; Stobova and Stephenson, 2002). These intracontinental basins have evolved under tectonic conditions allowing salt structures to grow under regionally homogeneous stress conditions. Salt basins in other tectonic domains, such as fold and thrust belts or passive margins, have undergone different tectonic conditions controlling the development of salt structures.

In recent decades, focus has shifted to the margins of continents where prolific hydrocarbon systems are present. Many continental margins have accumulated significant salt (evaporite) deposits during the transition period from crustal extension to seafloor spreading (Hudec and Jackson, 2007; Jackson and Hudec, 2005). Thermal subsidence dominates during the subsequent passive margin evolution introducing a slope towards the evolving oceanic lithosphere. The developing slope gives rise to lateral displacement gradients, which are superimposed by sedimentary loading and eventually propagate into the evolving accommodation space (Fig. 1). Gravity is the driving force in these passive margin systems, imposing an overall lateral displacement field that differs significantly from the vertical gradients in intracontinental settings (Fig. 1).

Salt Tectonics in the Brazilian Margin: Key Issues and Technical Advancements in the Past 30 Years

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Abstract

The Brazilian salt basins belong to the South Atlantic salt province formed in the Early Cretaceous as a consequence of the Gondwana breakup and extend from the southern Santos basin towards the Sergipe-Alagoas basin in the northeast. Salt tectonics studies in the past 30 years resulted in outstanding technical advancements and a much-improved understanding of salt sequences distribution along the various sedimentary basins along the eastern Brazilian margin. This has led to giant hydrocarbon discoveries in the ultradeep water regions of several salt provinces, particularly within the Santos, Campos, and Espírito Santo basins. This work addresses some of the key issues in the salt tectonics studies developed in the southeastern Brazilian margin in the past few decades, focusing on alternative interpretations of the Cabo Frio fault zone, between the Santos and Campos basins, the stratified evaporites in the distal Santos basin, the allochthonous salt play in the northern Espírito Santo basin, and strike-slip salt tectonics associated with the Frade Field in the northern Campos basin.

A Critical Review of Models for Deposition of the Louann Salt, and Implications for Gulf of Mexico Evolution

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Abstract

Two interpretations drive models for Louann salt deposition in the Gulf of Mexico. First, it appears that salt at the landward edge of the basin was deposited near sea level. Second, it appears that salt at the seaward end of the basin was deposited at oceanic depths shortly after salt deposition.

Three published models for Louann salt deposition attempt to reconcile these interpretations. In the outer-marginal-collapse model, salt was deposited at sea level in a basin undergoing rapid tectonic subsidence. Continued subsidence after salt deposition tilted the basin seaward, placing the downdip end in deep water. In the postsalt-crustal-stretching model, salt was deposited in shallow water in a pre-existing depression, eventually filling the basin to sea level. Crustal stretching after the end of salt deposition thinned the salt, eventually dropping the center of the basin down to depths comparable to oceanic crust. Finally, the high-relief-salt model suggests salt was deposited in a basin having several kilometers of depositional relief.

Each of these models has drawbacks in the Gulf of Mexico. For the outer-marginal-collapse model, numerical simulations of rifting do not produce the abrupt, late-stage collapse required by the model. For the postsalt-crustal-stretching model, there does not appear to be sufficient late-stage crustal extension. The high-relief-salt model requires a type of salt deposition for which there are no modern analogs. More data, especially from the downdip ends of the salt basin, would help narrow down the possibilities or contribute to a new model.

Salt Tectonics Controls on Deepwater Sedimentation: Salina del Istmo Basin, Southern Gulf of Mexico

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Abstract

The Salina del Istmo Basin, also known as Campeche Salt Basin, is characterized by a complex structural evolution controlled by a combination of salt tectonics, gravity-driven extension, onshore uplift, and regional shortening. There are only a few studies in the southern Gulf of Mexico and these are mainly based on sparse 2D regional seismic lines. Due to the structural complexity and the lack of previous studies, it is unclear how primary salt movement alone and in combination with regional tectonic events has controlled the distribution of reservoir-prone sediments. Based on a basinwide (71,000 sq. km) 3D seismic interpretation, we reveal new insights about the temporal and spatial variations of deep-water sedimentation and the exploration significance basinward (water depths ranging from 250 m to 3750 m) of the 2017 Zama-1 oil discovery. The data consists of a 3D wide-azimuth, broadband depth-imaged seismic reflection volume acquired between 2015 and 2017.

The present day structural and stratigraphic complexity of the basin is illustrated by folding, thrusting, and complex dissection of submarine channels, depositional lobes, and mass transport complexes. Nevertheless, detailed seismic stratigraphic mapping and geomorphological analysis suggest that primary salt movement started in the Eocene and continued during the Oligocene. During this initial phase, salt-related highs locally diverted and laterally and frontally confined deep-water depositional systems.

Further confined sedimentation continued in the lower Miocene resulting in local welding of primary minibasins, inversion of minibasin stratigraphy, and the formation of turtle structures. These observations are also locally recognized in isopachs and seismic attributes below allochthonous salt sheets and canopies. Orogeny-driven shortening events in the Miocene led to further lateral and frontal confinement of deep-water depositional systems within relatively smaller shortening-related minibasins. The development of shortening-related minibasins was locally accompanied by secondary welding and the emplacement of allochthonous salt sheets and canopies due to shortening and salt expulsion from bounding salt diapirs.

Salt tectonics controls during the evolution of Salina del Istmo Basin have direct implications on reservoir distribution and architecture and trapping styles; thus, these observations should be recognized and considered during further hydrocarbon exploration and development of this frontier basin.

Controls of Interbedded Sand Beds on Pore Pressure, Stresses, and Evolution of a Salt System

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Abstract

We use a 2D forward finite-element model to simulate how a salt wall rises, forms a salt sheet, and finally welds along its feeder in a basin under tectonic shortening for end-member mudrock basins with and without interbedded sands. We begin with a flat 3X60 km salt layer and sequentially deposit layers of sediments that dip toward the center of the salt layer at a constant base-level-rise rate. Shortening begins after a salt diapir rises to the basin surface at the center. In the model with sand beds, sands extend laterally across the basin to the salt diapir and have a uniform initial thickness of 100 m and a vertical spacing of 1 km far from the salt wall. Sands and mudrocks both have a poro-elastic-plastic behavior, but sands have different compressibility, higher friction angle, and orders-of-magnitude higher permeability than mudrocks. We show that sand beds significantly affect pore pressure, stresses, and evolution of the salt system. However, their effects differ substantially before and after the emplacement of the salt sheet.

Before a salt sheet forms, sand beds, dipping away from the salt wall sub-parallel to the wall's flank, focus pore water flow along the beds toward the salt wall, (1) increasing pore pressure at the crest of sands and encasing mudrocks near salt; (2) decreasing the sealing capacity of the mudrocks; and (3) decreasing the margin of appropriate mud weights for drilling wellbores near salt. In contrast, after a salt sheet forms, sand beds above the diapir's feeder, extending to and dipping toward subsalt areas, focus the flow away from these areas, decreasing pore pressure and increasing the sealing capacity and appropriate mud weights subsalt. The overall magnitude of overpressure and porosity is lower in the basin with sand beds because sand beds below the diapir's feeder hydraulically connect deep sediments far from salt to subsalt sediments, and sand beds above the feeder in turn connect subsalt sediments to the basin surface, substantially shortcutting the drainage path of pore water in the basin and thereby resulting in higher overpressure dissipation and basin compression.

We show that at early stages of shortening, when the diapir's feeder is wide, salt expulsion from the diapir requires minimal lateral pressure on the diapir, so the salt diapir is far more deformable than the basin and most of the shortening is accommodated by the diapir shortening. In contrast, at the late stages of shortening, when the diapir's feeder is narrow, viscous resistance against the salt flow through the feeder is substantially high, requiring dramatic lateral pressure on the diapir to expel salt; consequently, the diapir is less deformable than the basin and most of the shortening is accommodated by basin shortening through upturning against the diapir. Because the basin with sand beds has less overpressure and higher effective stresses, it is stiffer and upturns less, resulting in a thicker salt sheet to form in the basin with sand beds.

Redirection of Submarine Channels by Minibasin Obstruction on a Salt-Detached Slope: An Example from Above the Sigsbee Canopy

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Abstract

As minibasins subside and translate down salt-detached slopes in the presence of significant base-salt relief, they may weld and be unable to freely translate downslope. As salt and unwelded minibasins farther updip continue to move downslope, they may converge with, weld against, or overthrust the obstructed minibasins. How these processes modify seafloor topography remains unknown. In this study, we examine how obstruction of minibasins can modify seafloor topography and reroute deep-water depositional systems.

Seismic attribute analysis reveals how a submarine channel system evolves as it passes through a cluster of supra-canopy minibasins in the mid-to-lower slope, before spilling onto the continental rise. At an early stage, the channel system trends broadly slope-parallel, spilling straight onto the continental rise. However, at a later stage, the channel system is deflected through 90° in the frontal minibasin to trend broadly slope-perpendicular, shifting the locus of deposition on the continental rise by ~20 km. We use growth strata and seismic-stratigraphic relationships within the minibasins to determine that deviation of the channel system is broadly coeval with the basal welding, and hence obstruction, of part of the frontal minibasin, and overthrusting of this portion of obstructed minibasin by an unwelded minibasin on its updip side. We argue that overthrusting of the frontal minibasin increases the tectonic load and enhances the subsidence of its updip side. This topographic lowering then captures sediment gravity currents that otherwise trend slope-normal, causing rerouting of the associated submarine channel system and a shift in the depositional locus on the continental rise.

We show that zones of shortening upslope of obstructed minibasins do not simply act as persistent seafloor topographic barriers to downslope sediment routing, as is implied in simple 2-D, fill-and-spill models. Instead, we argue that a more three-dimensional, dynamic salt-tectonic framework is required when assessing deep-water sediment dispersal on salt-influenced slopes.

The European Zechstein Salt Giant—Trusheim and Beyond

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Abstract

The work of Trusheim in the early 1950s in the German Zechstein Salt Basin laid the foundation for interpreting the kinematic evolution of salt structures. His observations connected salt diapir evolution to sedimentation. This paper shows examples of how our understanding from Trusheim to today has evolved in the Zechstein salt giant. We discuss later interpretations of Trusheim's work and show that his ideas were closer to our current models than usually thought. Since then, we have seen enormous progress in understanding of the driving mechanisms, kinematics and geometries of salt tectonics, but still much can be done in understanding dynamics. Our knowledge of salt basins has grown mainly by hydrocarbon exploration and production to define the external shapes and kinematics of salt structures, while the search for nuclear waste disposal and salt mining explored the internal structure of salt.

We review work in the Zechstein in the past two decades which combine geology, geophysics, geochemistry, salt rheology, geomechanics, structural retro-deformation, finite element modeling and analog modeling towards a more integrated approach to salt dynamics. We show examples of detailed case studies of multiphase salt tectonics, with 3D seismic linking the external and internal structures at scales from 10 m to 100 km, and sedimentary response to multiphase salt movement. The understanding of internal structures of the evaporites, their relationship with salt rheology, and fluid flow through salt at scales of nm to km has contributed to better prediction of subsurface integrity, avoidance of drilling hazards, design of salt caverns, and the quest for nuclear waste repositories.

3D Model of Complex Internal Structures in a Northern German Salt Diapir: A Multidisciplinary Approach Using Drilling Cores, Well Logs, and Ground Penetrating Radar

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Abstract

The detailed internal compositions of salt structures are typically difficult to determine because they are poorly imaged on seismic reflection data and rarely exposed in field outcrops. Only a few studies have revealed detailed data of the internal structures from mine excavations. In a North German salt diapir, there are plans to expand one of these mines. For this purpose, detailed geological information of the salt structure is necessary. Because saline solutions have flooded two neighboring mines, special care needs to be taken when deciding where the new mine openings can be constructed.

In this study we use borehole data and drill cores plus ground penetrating radar (GPR) for site investigation. Detailed core description, microscopic and mineralogical-geochemical analyses allow a reliable lithostratigraphic classification of the Permian (Zechstein) evaporites penetrated. Structural analysis of well logs and GPR data document the spatial arrangement of the strata. The multidisciplinary evaluation of different data sets lead to an improved understanding of the evaporite composition and structure. The degree of matching of all exploration data in a new high resolution 3D model as well as an integrated analysis allows an estimate of the plausibility of the interpretation. Furthermore, the model can be used to assess the salt structure as a whole as well as to plan future exploration work and new mine excavations.

Based on the new data, an updated interpretation deviates considerably from the prior geological model of the salt structure in the investigated area. The old model predicted relatively pure halite in a large scale anticline. However, complexly folded younger units containing a number of 1-2.5 meters thick anhydrites were discovered. This study highlights that structural styles can vary abruptly along strike in a salt diapir. The identified structures indicate the kinematics of a multiphase salt rise. We show that regional compression and inversion tectonics played a key role in the diapir growth. They also affected the salt structure outer shape and lead to complexly folded as well as partly overturned Zechstein strata.

Salt Tectonics and Hydrocarbon Accumulations Trapped on Diapir Flanks in the Lusitanian Basin, Portugal

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Abstract

Salt movement in the Lusitanian basin has significantly affected sedimentation in the onshore portion of the basin. We show that salt diapirism initiated soon after deposition of the salt in the Hettangian and that diapirism was active throughout the Jurassic and Cretaceous periods. Strong Alpine-age inversion produced squeezing of the diapirs and folding and faulting in the overburden around the salt structures. Large upturned flanks of overburden sediments were produced and constitute good potential traps for hydrocarbon accumulations. We describe two upturned diapir flanks which are superbly exposed on coastal cliffs. Both the São Pedro de Moel and Santa Cruz structures contain tar-saturated reservoirs, trapped against salt diapir walls. We interpret these to be exhumed but now biodegraded, oil accumulations. The São Pedro de Moel structure is estimated to contain >85 million barrels of tar and demonstrates that there is a commercially viable hydrocarbon system in the basin, although most of the traps onshore have been breached during inversion. This has positive implications for the deeper offshore Lusitanian and Peniche basins, as well as the conjugate Carson-Bonnition basin in Newfoundland. To our knowledge these are the only documented examples of exposed hydrocarbon accumulations trapped against salt diapir flanks and could represent the first bygone oil accumulations described in the Lusitanian basin.

Salt Tectonics Outcrops and 3D Drone Images from the Sivas Basin (Turkey) Compared to High-Resolution Seismic Lines in the GOM and B32 Angola

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Abstract

The outstanding outcrops of salt tectonic structures of the Sivas basin in Anatolia are now well-known. A drone acquisition in November 2018 provides 3D images to visualize and interpret the structures in order to better analyze subsurface data from salt domains. Drone images, now widely used in structural geology, allow building 3D qualitative models of the outcrops. Seven structures among the most demonstrative of salt tectonics have thus been imaged in secondary minibasins.

The Sivas basin, an elongated Oligo-Miocene north-verging multi-phased foreland basin, developed above the Neotethys suture zone. Evaporites deposited at the end of the early compression phase (Bartonian), filled the foreland basin and covered eroded thrust sheets and folds to the south. Primary minibasins formed during a period of quiescence from Late Eocene to Early Oligocene, associated to the building of an evaporite canopy. The system further evolved during convergence of the Arabian and Eurasian plates in the Late Oligocene-Early Miocene with a renewed compression on the north verging fold-and-thrust belt (FTB). This resulted in the formation of secondary minibasins, ultimately tilted and welded.

In the last decades, huge improvements in seismic imaging under thick allochthonous salt have been made in the Gulf of Mexico and Angola. Wide-azimuth towed-streamer (WATS) 2D as well as 3D seismic acquisitions allow far better imaging along steep subsalt diapiric flanks and welds. However, major drilling disappointments still do occur, due to unseen megaflaps and small-scale structures such as halokinetic sequences at various scales or small faults cannot be seen. Field analogs then become the only guide for a better assessment of the traps.

Striking geometric analogies between the Sivas outcrops and seismic images from the classic petroleum provinces controlled by salt tectonics will illustrate the extraordinary quality of the Sivas basin as a geometrical field analog for the Angola and the Gulf of Mexico salt basins. Analog modelling imaged with X-ray tomography under a medical scanner will also be used for comparison (Callot et al., 2016).

Salt Tectonics Restoration in Basin and Petroleum System Modeling: Contribution of Physical Analogue Models and Methodologies

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Abstract

Being able to reproduce the tectonostratigraphic evolution of a basin is crucial to accurately reproduce the structural, thermal, pressure history of the basin, and its associated petroleum system(s). When salt movement is involved, the structural reconstruction becomes even more challenging. The objective of this paper is to show how physical analog modeling can help to understand the structural complexity observed in salt tectonics. When correctly scaled, analog sand/silicon models add some constraints to the chronology of deformation necessary for a convincing restoration scenario. Two methods of backward salt sequential restoration, the classical pure vertical shear backstripping and more recently developed structural restoration accounting explicitly for lateral movements along faults, have been tested. Results are presented on 2D and 3D basin model examples. Though much progress has been made, sequential salt restoration still remains challenging. On one hand, efforts are concentrating to set up fully automatic approaches. On the other hand, developments are performed to produce more flexible and adaptable meshing technologies that will lead to more realistic geometric evolutions through time, as well as more accurate estimations of fluid flow and mechanical stresses.

Loading Complex Salt Isopachs: Progradation Across Segmented Salt-Filled Rift Systems

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Abstract

Deposition of salt during, or immediately after, crustal extension adds to the complexity of post-deposition salt tectonics in many ways. For example, salt may be thin or absent across intra-rift highs, thus impacting mobility and connectivityand influencing deformation styles during subsequent sediment loading. We use physical models to investigate salt-tectonic processes in sediment-driven remobilization of a complex salt isopach within a segmented rift system. A stretching rubber sheet generated regional extension (Fig, 1). Slabs of weak silicone embedded at the base of the pre-rift stratigraphy localized extension to produce a series of soft-linked discrete graben (Fig. 1). Model salt filled the deep graben, thinning across linkage zones. The horst blocks between grabens were either covered with a thin salt fringe producing a complex, but connected, salt isopach (Model 1; Fig. 2), or salt was entirely absent above these highs producing a highly complex and segmented salt isopach (Models 2 and 3; Fig. 5). The salt basin was tilted and loaded by a series of sedimentary wedges. Distal aggradation gradually buttressed the prograding system and thickened and strengthened the suprasalt roof.

Although impacted by the structural relief at base salt, mobility was aided in models where a continuous salt fringe covered the entire basin, resulting in extension and translation of the sedimentary overburden (Model 1, Figs. 2-5). Large salt walls formed downdip of the toe of the sedimentary wedge as seaward-flowing salt was buttressed against the edges of deep graben (Figs. 3a-c). Continued thickening of these salt-cored uplifts eventually allowed them to collapse and translate seawards under extension (Fig. 3d). Sedimentary loading of these extending, flat-topped diapirs formed local minibasins that translated seawards until they welded atop subsalt strata, freezing the adjacent diapirs in place (Fig. 4b). Diapirs were also deformed as they passed through extensional and contractional hinges associated with topographic monoclines developed above the horst and graben topography in subsalt strata (Fig. 4b).

In models where salt was absent across structural highs (Models 2 and 3, Fig. 5), major intra-basinal high blocks formed significant barriers to lateral salt mobility, trapping significant volumes of salt in the graben, especially where the salt was depositionally thin and/or the suprasalt roof was thickened by aggradation and resisted breaching (Fig. 6). These horst blocks are also commonly sites of diapirism, where the salt budget is sufficient, as salt displaced by the sedimentary load is again contractionally thickened against these flow barriers (Fig. 7). Minor or narrow horst blocks are less of a barrier to seaward salt displacement, allowing salt expulsion from one graben to another, and vertical stacking of salt bodies and canopy formation where the salt budget is high (Fig. 8). Stepped counter-regional systems dominate in these segmented salt basins with limited extension seen at the autochthonous level, although roho extension is seen above some canopies prior to welding (Fig. 8). In both suites of models, portions of the rift zone having more subdued structural relief (e.g., transfer zones accommodation zones), and thus better salt connectivity, help facilitate seaward salt expulsion (Figs. 4a and 9).

Despite the inherent oversimplifications in our physical models, some good first-order similarities are demonstrated between our results and seismic-based examples from the Scotian margin (Figs. 10 and 11).

Geomechanical Modeling of Diapirism in Extensional Settings: Controls on Styles of Diapir Rise and Fall

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Abstract

We develop large strain, transient evolutionary geomechanical models of salt extensional systems to study possible controls on styles of diapir rise and fall. We examine extension rates of 1 and 2 km/m.y., base-level rise rates of 1km/5m.y. and 1km/3m.y. and basement slopes of 0°, 1°, and 2°. We find that high sedimentation rates and low extension rates promote efficient sweep of salt from the source layer into the diapir(s). This favors the development of a single structure and leads to taller diapirs that eventually develop sharp corners. We show that growing diapirs load wall rocks laterally and increase their horizontal stress despite the imposed regional extension. In contrast, basement slope and increasing extension rates lead to inefficient salt sweep. We show that this inefficient sweep results in partitioning of the extensional strain across the basin and development of multiple diapirs with extensional turtle structures between them. Horizontal stresses remain low across the basin. We also study possible styles during diapir collapse. We show that the presence of sharp corners (bulb shape) in a diapir favors synclinal collapse. This is because the corners in a bulb-shaped diapir act as stress concentration points and cause weak fault zones to radiate upwards and isolate the roof above the falling diapir. Horizontal stress in the roof sediments between the faults increases and differential stress decreases. We compare our geomechanical observations with similar kinematic features found in the field, as well as with features found in physical models.

Structural Configuration and Evolution of Subsalt Hydrocarbon Traps Adjacent to Salt Walls, Green Canyon, Gulf of Mexico

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Abstract

Seismic and well data are used to constrain the geometry and evolution of an oil field located adjacent to a salt wall in the Green Canyon protraction area, northern Gulf of Mexico. Full and wide azimuth 3D seismic data image the configuration of the salt-sediment interface (SSI) and structure of the field: a three-way trap developed along a salt wall/weld system. Data from wells drilled to appraise and develop the field are used in conjunction with the seismic data to constrain the structural interpretation and trap geometry. Well data utilized in the study include: biostratigraphic age control, wireline based sand and marker correlations between wells (with supporting information from detailed geochemical analysis), and bedding orientations from core and logs (resistivity and oil-based image logs). Wells are drilled in water depths of approximately 1.5-1.8 km (5,000-6,000 ft) targeting a subsalt reservoir in Miocene turbidite sandstones. Wells penetrate a salt canopy up to 5 km (3 mi) thick overlying the objective section. The field occurs in a dipping halokinetic sequence (dip magnitudes range from ~20° to overturned). The interpretation indicates that the reservoir sand interval pinches out before intersecting the SSI. Two general populations of sub-seismic scale structures (deformation bands and small offset faults) are observed in core and image logs from wells adjacent to the salt weld: one population in which deformation bands and faults trend approximately parallel to the strike of the SSI; and one in which these features trend at a high angle to the SSI. The population that trends at a high angle to the SSI occurs in the vicinity of a change in megaflap geometry and a change in trend of the SSI.

Sub-Seismic Deformation in Traps Adjacent to Salt Stocks/Walls: Observations from Green Canyon, Gulf of Mexico

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Abstract

Well data are used to constrain the sub-seismic deformation of two oil fields trapped against a salt wall in the Green Canyon protraction area, northern Gulf of Mexico. Two general populations of sub-seismic scale structures (deformation bands and small offset faults) are observed in core and image logs. One population of deformation bands and faults trend approximately parallel to the strike of the salt-sediment interface (SSI) and are observed where the SSI is relatively linear. A second population of features that trend at a high angle to the SSI occur in the vicinity of a change in flap geometry and associated change in trend of the SSI. This later population is more important for reservoir compartmentalization and flow baffling.

Can Deep Mantle Processes Influence Regional Salt Tectonics?

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Abstract

Mantle processes produce uplift (over mantle upwelling) and downwarp (over downwelling) that are of more or less equal vertical and spatial magnitude. Mantle uplifts have been recognized in both the present day and geological past because they have an obvious effect recorded by erosion and fluvial incision patterns. Modern downwarped regions can be identified by anomalous bathymetry, but identification in the geological past is difficult.

Previous studies have considered the effect of mantle uplift on fluvial processes and sediment budgets, but the effects of downwarping have received little attention, and the potential impact of an upwarp-downwarp pair on salt tectonic processes has not been previously described.

Vertical offset of the ground surface is 1-2km. Vertical movement is magnified by the effects of erosion/deposition, and it may exceed 5km. Vertical movement occurs over a 1-10 m.y. time frame; most rapid uplift is at the million-year scale. Affected regions are broadly circular, on a 500-1,000 km scale. Associated tilting ranges from 0.1 to 0.5 degrees. This might appear to be an insignificant influence on salt tectonics, but there are several reasons why regional tilting may be important. We consider a margin in which the basin is downwarped and the hinterland is uplifted.

Direct effect: Although the gradient change is slight, because it is sustained over a whole slope it may trigger changes of behaviour. A passive-margin coulomb wedge at the point of failure may be pushed into overall internal failure. Minor tilting of gravity-gliding systems having near-horizontal basal surfaces greatly increases the energy released by gliding, potentially resulting in increased slip rates.

Indirect effect: The indirect effect is felt through the migration of facies belts at the shoreline and major redistribution of sediment. Net sediment flux increases because uplift of the hinterland causes increased erosion and sediment supply; fluvial systems are extremely sensitive to gradient, so tilting is likely to result in stripping of older continental sediments and rapid transport of the erosion products to the shelf edge and slope. Regional tilting can trigger mass failure of the upper slope/shelf margin resulting in shelf-margin break up and the release of large volumes of sediment downslope. Turbidite depositional systems are acutely sensitive to changes in slope: sustained 0.5 degree tilt may change an entire slope from net deposition to net bypass. The overall effect is likely to be a major increase in sediment supply to the lower continental slope and rise, fundamentally changing the sediment load on subsurface salt.

Case studies: we suggest that Palaeocene and Miocene mantle uplift of the western US and downwarp of the U.S. GoM resulted in simultaneous and drastic change in deposition (onset of Wilcox clastics) and change in salt tectonic style (e.g., renewed motion of the deep salt nappe, and development of Paleocene and Miocene frontal fold belts). In Angola, mantle driven uplift of the Bié-Huila dome is coincident with a major late episode of slope-scale basinward slip and a significant increase in clastic sediment flux to the deep water. We suggest that these are a direct consequence of the regional low-angle tilting.

We also discuss the implications for sediment flux to the shelf margin and the resulting deep-water processes in the Gulf of Mexico of a paired system of mantle-driven upwarp and downwarp that was active during the Paleogene and Miocene. We propose there is a characteristic stratigraphic signature of the deep mantle processes discussed here.

Mass-Transport Complexes (MTCs) Steered by Minibasin Obstruction and Extensional Breakaway on a Salt-Detached Slope: An Example from Above the Sigsbee Canopy

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Abstract

In salt-detached slopes, minibasins translate downslope as they subside into salt. If the base of salt has high relief, minibasins may weld and stop translating downslope. An unwelded minibasin can pull away from an obstructed minibasin located farther updip, forming an extensional breakaway zone. How this process can affect seafloor topography is still unknown. In this study, we examine how extensional breakaway zones associated with minibasin obstruction can modify seafloor relief and therefore affect the routing of slope depositional systems.

Using a 3D seismic data set, we investigate the routing of a mass-transport complex (MTC) through a cluster of supra-canopy minibasins in the mid-to-lower slope and onto the continental rise. The MTC is initially transported slope-parallel before reaching the minibasin at the slope toe. At a later stage, growth of an extensional fault system causes formation of an intra-slope topographic barrier and deflection of the MTC into an adjacent minibasin.

Kinematic analysis of the fault system and seismic-stratigraphic relationships show that: (i) the extensional fault system formed in response to basal welding of an updip minibasin; (ii) minibasin welding pre-dates the MTC deflection; (iii) welding-related extensional fault system was initiated farther downdip away from the MTC path and propagated along-strike towards the MTC path; (iv) when the extensional fault system reached the MTC path, salt-buoyancy assisted uplift of footwall block occurred and formed a topographic barrier that deflected the MTC; and (v) deformation within the extensional fault system was accommodated as differential translation of the salt canopy onto the continental rise.

Our findings highlight the complex geometry and kinematics of extensional breakaway zones associated with minibasin obstruction and the role that normal fault growth and along-strike propagation has on MTC dispersal. Our study illustrates how salt-tectonic processes related to minibasin obstruction can modify slope topography and control deepwater sediment dispersal.

Interaction of Tectonics, Salt, and Sediments in the Gulf of Mexico: An Approach Using Image Processing of Seismic Data

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Abstract

The interaction of salt tectonics and salt movement as well as their combined interaction with sedimentation has implications on the formation of reservoir distribution and formation of traps in the Gulf of Mexico. I have used the approach of image processing of seismic data that loads triplets of adjacent depth slices from the seismic data cube into red-blue (RGB) images and processes these RGB images with image processing techniques. The method generates color images of impedance contrast correlation at single seismic sample resolution. Using this method, I have created color image cubes for seismic data from the Sigsbee Escarpment. They reveal geological phenomena having a similar clarity to that of satellite images. These example images allow us to study the interaction of tectonics and salt migration, which in turn, jointly interact with sedimentation that has implications on the formation of reservoirs and traps in the Gulf of Mexico.

I have studied the interaction of tectonics with salt where the salt has moved close to the sea floor. Shear faulting breaks up the protective caprock thus exposing the halite to dissolution by the undersaturated sea water. The caprock collapses where shearing faults enter the evaporite body leaving characteristic salt karst dolines. In relatively deeper strata, the faults crack the caprock, which has resulted in the deposition of the caprock boulders on the ancient sea floor and may represent a potential drilling hazard.

The interaction of the salt with sedimentation has been studied on seismic data as well. Local salt movement tilts the seafloor, thus destabilizing the unconsolidated seafloor sediments. The high vertical resolution of 5 to 10 m of the image-processed seismic data reveals different stages of sea floor instabilities from slides to fully developed mass transport systems. Such processes have also been delineated in deeper formations in the same data cube and may be used to reconstruct the ancient tectonic stress.

Finally, the interaction of regional tectonics with flow features within the mass transport systems has been studied. Incised sections of mass transport complexes are correlated in locations where shear faults affect salt flow. Large gravity slides of contiguous section of the unstable seafloor occur along regional faults.

The movement of salt can destabilize unconsolidated sediments at the seafloor resulting in redistribution of porous clastic sediments in turbidite channels. The tectonic overprint of these channels can create traps for hydrocarbons.

The Sakarn Series: A Proposed New Middle Jurassic Stratigraphic Interval from the Offshore Eastern Gulf of Mexico

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Abstract

The quasi-conformable succession of Middle to early Upper Jurassic (Callovian to Oxfordian) within the onshore Gulf of Mexico Basin has classically been described as follows: the Werner Anhydrite is the basal member of the Louann Salt and lies above a subcrop of older Mesozoic and Paleozoic rocks. The Norphlet Formation overlies the Pine Hill Anhydrite Member of the Louann Salt and in turn is overlain by the Smackover Formation. However, analysis of the seismic stratigraphy in the offshore region of the eastern Gulf of Mexico Basin (EGoM) has revealed the presence of a sedimentary succession up to 2,500 meters (~8,000 feet) thick above the Louann Salt, laterally adjacent to the Norphlet Formation, and below the Smackover Formation. Based on the seismic stratigraphy, this newly recognized interval, which the authors refer to as the Sakarn series, is considered to be older than the Smackover Formation and coeval to the Louann Salt.

There are no well penetrations within the Sakarn series. The Sakarn series is interpreted on 3D seismic volumes predominantly in the Lloyd Ridge Outer Continental Shelf (OCS) protraction area, southeast of the current offshore Norphlet exploration trend, and is underlain by either Louann evaporites or welded salt. Deeper stratigraphy below the Sakarn series and/or the Louann Salt is interpreted as a pre-salt rift succession. The mapped area includes the Sakarn domain, which is limited by abrupt lateral termination of the Sakarn series against major structural features, either normal or transform faults, which were important lineaments during the early opening phase of the Gulf of Mexico Basin in the Middle and Late Jurassic; they limit the present day distribution of the Sakarn series.

Regional paleogeographic context of the Sakarn series places its deposition in low-middle latitudes during an overall extremely dry climate, indicated by Louann evaporites and the aeolian-fluvial, partially evaporitic Norphlet Formation. The seismic character of the Sakarn series exhibits multiple frequency contrasts and several high velocity intervals. Anhydrite, carbonates, shales, and siliciclastic sediments are all possible given observed seismic attributes.

There is no consistent or accepted published biostratigraphy for both the Louann Salt and Norphlet Formation. The Louann Salt has been classically placed in the Callovian stage of the Middle Jurassic (Salvador, 1987; Mancini et al, 1985; 163.5Ma to 166.5Ma; Gradstein et al., 2012), a duration of 2.6 m.y. Biostratigraphic data in onshore and offshore wells provide a Middle Oxfordian age for the Smackover Formation, which constrains the age of the Norphlet Formation as no younger than ~161 Ma. The units of the Sakarn series are therefore older than 161 Ma, but lack biostratigraphic constraints on absolute age and duration.

The Louann Salt, the Sakarn series, and the Norphlet Formation could collectively represent rapid deposition during the Callovian to Early Oxfordian, perhaps >10,000 feet in a few million years. Alternatively, the thick Sakarn series and its seismic layering indicate a potential significant time period for its deposition, implying our current understanding of Middle-

Upper Jurassic stratigraphic evolution of the EGoM may need to be revisited. Extending the onset of Louann Salt deposition to the Bathonian (170.3Ma to 168.3Ma) or earlier may be considered and is postulated to be supported by historical strontium isotopic analytical data (Pulham et al., 2019)

A revised stratigraphic chart and paleogeographic evolution of the Middle Jurassic is proposed to integrate the Sakarn series with a tentative and broad age bracket of within the Bathonian to perhaps earliest Oxfordian, including the underlying Louann Salt depositional episode and overlying Norphlet Formation; a total time period of up to 9 m.y.

Salt Canopy Rafts in the Northern Gulf of Mexico: Identifying and Understanding the Significance of Strata Laterally Translated by Allochthonous Salt

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Abstract

Identifying the age of sediment above allochthonous salt in the northern Gulf of Mexico can be challenging. To assist in understanding the section above the salt canopy, a model has been created to identify and categorize different age successions of supra-canopy strata. Salt canopy rafts (rafts) are defined here as stratal packages above allochthonous salt that are disconnected from primary minibasins and have moved a significant lateral distance from where they were deposited. Rafts are categorized by the age of the oldest strata present at their base in contact with allochthonous salt or its welded equivalent, and the different ages are related to their depositional origin. Mesozoic rafts have Cretaceous or Late Jurassic strata at the base and generally have been deposited on autochthonous or para-autochthonous salt. Paleogene and younger rafts are generally deposited on allochthonous salt; the basal age relates to the timing of canopy emplacement at their initial location. Minibasins containing salt canopy rafts have a different geologic history than basins containing only in place section. Therefore, recognition of rafted strata is required to understand the structural and stratigraphic development of suprasalt minibasins.

The relative thickness of raft strata is dependent primarily on the amount of underlying salt inflation or deflation during deposition. Relatively condensed intervals are deposited during or after underlying salt inflation or contraction and are very common. Relatively expanded intervals are deposited during or after underlying salt deflation or extension, and normal thickness intervals have been deposited while the underlying salt was stable. It can be difficult to establish normal thickness in areas of thick autochthonous and allochthonous salt. The most reliable estimates of normal or regional thickness are found where salt has never been present, such as the abyssal plain beyond the downslope limits of para-autochthonous and allochthonous salt. Strata deposited above autochthonous salt after welding also provide estimates of normal thickness, although this requires knowledge of the welding history. Strata deposited on the crests of turtle structures after welding of the underlying salt are usually a good location to estimate normal thickness. In practice, normal thickness estimates often contain uncertainty; however, going through the process of estimating normal thickness and considering the implications for where salt is inflating and deflating is a useful exercise that leads to a better understanding of the structural history.

In deep-water depositional environments, sedimentation generally occurs in all areas, even those that are topographically high due to underlying salt inflation. These topographically high areas typically receive reduced deposition that contains the finer grained fractions of the sediments being deposited, including the sides and tails of the turbidites, but often excluding the coarser grained components that are preferentially deposited in the topographic lows. Given enough time, these fine-grained deposits can accumulate to significant thicknesses up to several thousand feet in areas of active depositional systems.

Rafts of all types are most confidently recognized using wells plus 3D seismic tied to paleontological data that document repetition of suprasalt canopy strata below the salt canopy. Well logs from boreholes with incomplete paleontological data can be correlated to wells with paleontological data, and rafts that have not been penetrated by boreholes can be identified by correlating seismic character with drilled examples. In some cases, the complexity of suprasalt structural deformation near the base of the minibasin indicates significant lateral movement. The strength, character, and polarity of the top of salt can-

opy reflection in sediment flood volumes can also be used to distinguish between Mesozoic or younger section immediately above the salt.

Because Mesozoic strata contain significant thicknesses of carbonate lithologies that are generally faster than younger siliciclastic strata at relatively shallow burial depths, they also can be identified through careful application of tomographic velocity analysis and observations of weak and often uncertain polarity top of salt reflections. In the Gulf of Mexico, strong top of salt peaks in seismic data indicate the velocity of suprasalt strata is significantly slower than salt, which generally corresponds to Paleogene or younger section immediately above the salt. When Mesozoic section is present above the salt canopy, the top of salt reflection is typically a weak reflector of unknown polarity due to the low velocity contrast. The top of salt reflection beneath Mesozoic rafts will be a trough if the interval velocity juxtaposed with salt is faster than salt or up to approximately 10% slower than salt due to the significant negative density contrast between relatively high density carbonates and low density halite. These rafts show variable thickness of Mesozoic section and variable age of the oldest strata above the salt. The entire Mesozoic section in rafts is typically condensed, sometimes highly condensed, but not always. The detailed age of the strata immediately above the salt canopy ranges from Oxfordian to Early Cretaceous; Oxfordian is the oldest documented sediment deposited above the layered evaporite sequence in the Gulf of Mexico. The presence of strata younger than Oxfordian immediately above the salt in Mesozoic rafts is interpreted to be due to a combination of delayed onlap of sediments due to Mesozoic inflation of underlying salt and downslope movement associated with para-autochthonous canopy emplacement. Mesozoic rafts may also contain rafted Paleogene and younger section.

Paleogene and younger rafts have been deposited on allochthonous salt, the basal age relates to the timing of canopy emplacement at the location of initial deposition, and the salt sheet or canopy has developed during Paleogene time. Paleogene rafts are often encountered in areas where the local salt canopy formed during the Miocene, documenting significant raft translation from areas of Paleogene canopy located upslope. Paleogene rafts also contain rafted Miocene and younger section. Miocene rafts form on a salt sheet or canopy that initiated in Miocene time or earlier emplaced canopy salt that has been locally unroofed during Miocene time. Miocene, Paleogene, and Mesozoic rafts contain younger Pliocene or even Pleistocene age rafted section if they continued to move laterally with the salt after the end of the Miocene. Pliocene and Pleistocene rafts are also present in some of the relatively shallow suprasalt minibasins near the leading edge of the Sigsbee canopy where salt has continued to inflate and advance after the end of the Miocene. Expanded late Miocene, Pliocene, and Pleistocene suprasalt section is generally not rafted and is most often encountered in deep minibasins upslope of the leading edge of the Sigsbee salt canopy.

Careful application of the salt canopy raft model can provide a practical solution to the challenges of identifying age successions of supra-canopy sediments, appropriately modeling their geologic history, and accurately correlating rock properties and drilling hazards. The stratigraphic and structural relationships captured in raft strata document their geologic history, providing additional information on the regional geology of the Gulf of Mexico. Many rafts have portions that are nearly parallel bedded and condensed, but other parts of the rafts contain significant changes in thickness; growth strata record the underlying salt inflation and deflation history as well as structural deformation through time.

Rafts can rotate, undergo extension or contraction, or move laterally past each other during translation on allochthonous salt. Significant overriding of salt sheets can cause supra-canopy sediment to become encapsulated by salt. These encapsulated minibasins are often composed wholly or in part of rafts. The presence of rafted condensed section overlying the salt canopy in the bottom of many suprasalt minibasins shows that the earliest phase of minibasin development is often not caused by local thickening of strata above the salt but is instead a period of relatively condensed deposition on salt-cored topographic highs that occurred in a different location. These rafts are progressively translated with the canopy salt to their current position where salt deflation eventually occurred, although some thinner rafted minibasins do not show any significant salt deflation in their history.

Creating accurate structural restorations and basin models in areas with salt canopy rafts requires special attention. Not only is it necessary to properly identify the age and thickness of rafted strata, but it must be treated carefully during restoration and basin modeling. It is tempting to use the elevations of rafted sections to constrain the regional elevations and thicknesses of strata where there is no local subsalt control for structural restorations, but this leads to significant errors if the strata have been displaced laterally and vertically after deposition. Interpreting rafted section as in place leads to erroneously thick overburden above the source rocks and reservoirs in past time steps, inaccurately early estimates for hydrocarbon generation, and incorrect effective stress histories for reservoir quality predictions. Application of the salt canopy raft model leads to more accurate interpretation of the section above the base of allochthonous salt, which is critical for proper correlation of hazards from drilled examples to undrilled minibasins, and the interpreted interval thicknesses can be combined with regional well control to help guide predrill lithology estimates.