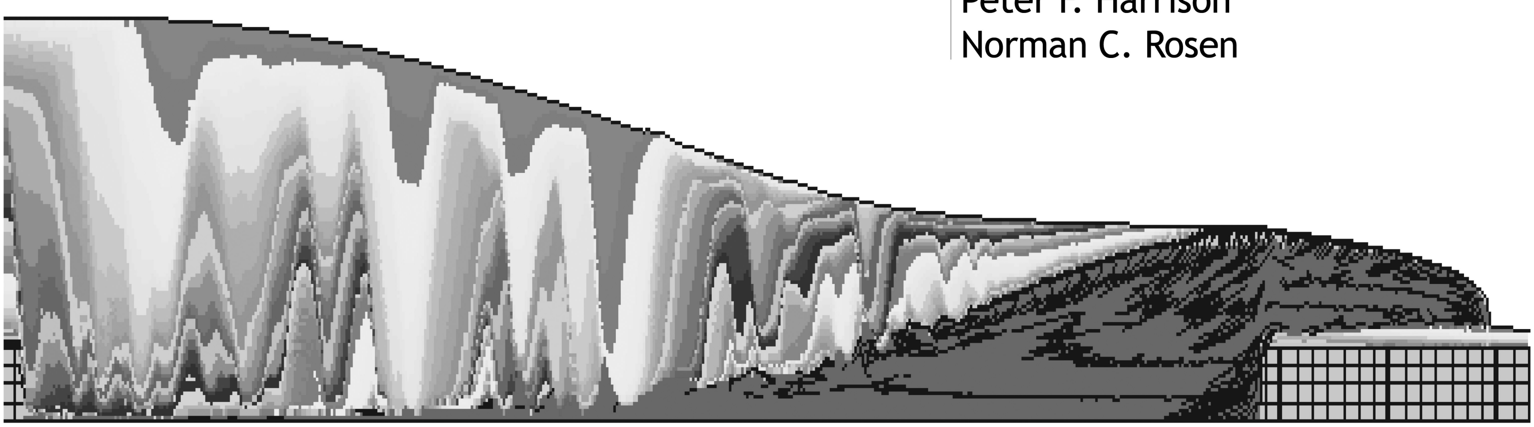
Salt-Sediment Interactions and Hydrocarbon Prospectivity:

Concepts, Applications, and Case Studies for the 21st Century

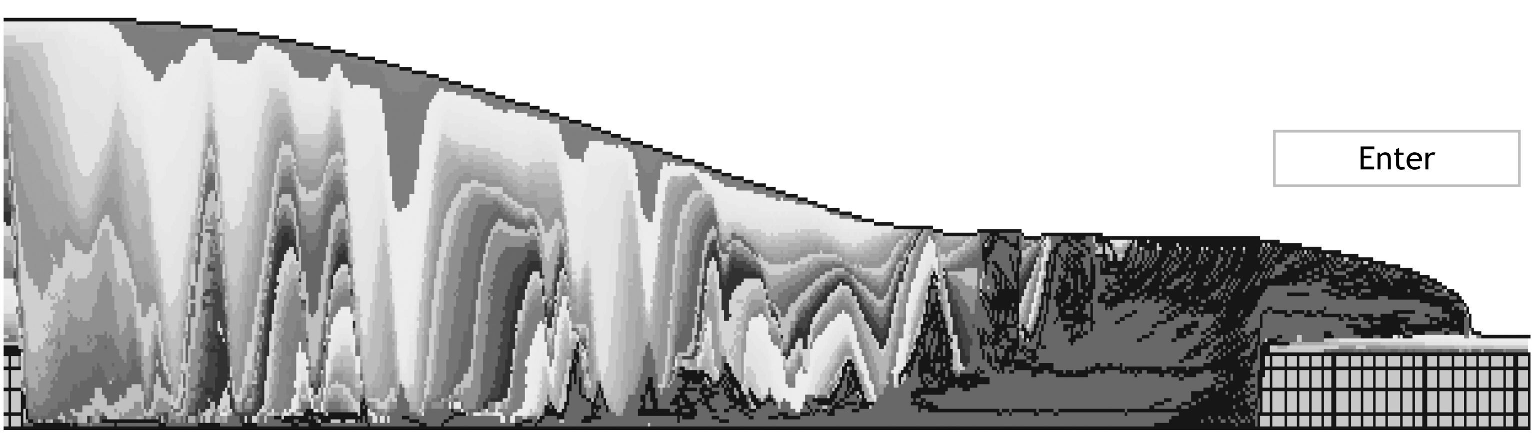
Program and Abstracts

December 5-8, 2004
Houston, Texas

Editors
Paul J. Post
Donald L. Olson
Kevin T. Lyons
Stephen L. Palmes
Peter F. Harrison
Norman C. Rosen



24th Annual GCSSEPM Foundation | Bob F. Perkins Research Conference



Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century

24th Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference

2004

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Paul J. Post, Donald L. Olson,
Kevin T. Lyons, Stephen L. Palmes,
Peter F. Harrison, and Norman C. Rosen

Published December 2004

Foreword

It had been too long. It was time: time for someone to propose, develop, and organize this conference. In 1995, GCSSEPM's 16th Bob F. Perkins Research Conference, "Salt, Sediment and Hydrocarbons" was held, and AAPG published "Salt Tectonics: a Global Perspective" with papers developed from a symposium held in 1993. The Geological Society published "Salt Tectonics" in 1996; and "Salt, Shale and Igneous Diapirs in and around Europe" in 1999. Five to ten years in the evolution of our knowledge of salt tectonics is too long. Concepts evolve and change. Salt moves.

To everyone who responded to an e-mail promising "If the conference goes well, you will earn the undying gratitude of the geological community" from someone they either knew, knew casually, or had no idea who was sending them the e-mail, yet agreed to serve as either a Program Advisory Committee Co-chair or a member of the Program Advisory Committee, thank you. Without each of you, your encouragement, advice, or paper, this conference would not have come into being.

We originally planned this conference around a series of themes that built upon each other. Unfortunately, as is often the case in life, our nice, neat themes did not correspond to the reality of what authors were able to provide. Consequently, for the final program, rather than force manuscripts into our themes, we altered the themes to fit the manuscripts. Mark Rowan, with his extensive knowledge of most of the authors, their backgrounds, and work, was instrumental in this retrofitting.

In today's exploration and production environment, and to some extent academia, there is seldom time to write papers. Many reasons are given, among them the fact that taking the time to write papers is seldom in anyone's yearly goals, and meeting and/or exceeding these can go a long way towards determining one's continued employment, or as someone said, "Real work gets in the way of good science." In addition to the time constraints there are increasing legal complexities necessary to obtain permissions from management, partners, and data owners. The hassle of publishing a paper soon becomes outrageous. Since GCSSEPM takes great pride in enriching the literature so that those who cannot attend our research conferences can benefit from the papers included in our programs via our conference CDs, the authors of all of these papers who devoted their time to produce them, often on weekends and after work, are the most important component of our research conferences. To each author and co-author, my sincerest thanks. Without your efforts, there would be no conference. On a similar note, my thanks to those companies and organizations that were supportive of members of their staff taking the time to write manuscripts and provide poster and oral presentations. The persistent efforts of authors, their organizations, and often their legal staffs, to obtain partner and/or government permissions to provide papers, was invaluable. To those vendors who allowed their data to be shown, my thanks.

To make it easier for authors to accept and incorporate reviews and edits, rather than editing hard copies, we requested that as many of our authors as possible submit their papers as MS Word documents. We circulated these to the editors and returned a single file to the lead author reflecting the work of all the reviewers. Our goal was to try to make the process of incorporating editorial changes as simple and time efficient as possible for the authors. They received a single MS Word copy back, could elect to hit the "Accept Changes" on the Reviewing Toolbar, and off they went, no more going from hard copy to hard copy trying to figure out which editor's comments to incorporate. It worked, or at least seemed to work, based on the comments we received from the authors.

Even the best writers need editors. Consequently, I would like to thank my Minerals Management Service colleagues, Don Olson, Kevin Lyons, Stephen Palmes, and Pete Harrison, who served as editors. Without their work, reviewing and editing 48 papers would have been impossible. We each learned from the experience. Minerals Management Service supported our efforts; allowing us to edit during work hours.

Norm Rosen encouraged me to convene this conference, and did his usual excellent job as final editor, so to one of my oldest and dearest friends, Norm, thank you. Even before Norm, Ed Picou was my sounding board regarding whether or not to consider attempting to convene this conference. Without his encouragement, I would never have undertaken this task. Minerals Management Service graciously allowed me to work on this conference as part of my duties.

My thanks to Ms. Jerri Fillon, who handles AV and is the calm in the eye of the chaos/frayed nerves/churning stomachs that can occasionally be the speakers' table. To all those "shoe maker's elves" who stuff bags, work at the registration table, and generally make sure that everything is done: without you, this parade does not hit the streets; to each of you my sincerest thanks.

To those few of you who actually read *Forewords* and the like, I trust I have not kept you too long from your real goal, the papers of this, the GCSSEPM 24th Bob F. Perkins Research Conference, *Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century*. Enjoy the fruits of our labors.

Paul J. Post

GCSSEPM Foundation

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Cover Image and Opening Animation

The cover image on the jewel case insert is from Ings *et al.*, Figure 4; specifically, the top image, which is a still image from his Model 2, demonstrating no density contrast between salt and overburden. The cover image on the Abstracts volume is from the entire Figure 4, comparing Model 2 and Model 1.

The opening animation for the CD is from Ings *et al.*, Animation 5, which demonstrates local isostatic compensation for the weight of the salt and sediments and assumed water loading above the sediments to the level of the prograding shelf.

Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century

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Houston Marriott Westchase
Houston, Texas
December 5–8, 2004

Program

Sunday, December 5, 2004

4:00-6:00 pm **Registration (Grand Foyer) and Poster Setup (Grand Pavilion)**

6:00-8:00 pm **Welcoming Reception and Poster Preview (Grand Pavilion)**

Monday, December 6, 2004

7:00 am **Continuous Registration (Grand Foyer)**

8:00 am **Welcome: Nancy Engelhardt-Moore, Chair of the Board of Trustees, GCSSEPM Foundation (Grand Pavilion)**

8:05 am **Introduction and Welcome: Paul Post, Program Chair (Grand Pavilion)**

Keynote Address

Co-Chairs: S.J. Kapoor and U.T. Mello

Session I—New Techniques in Modeling and Salt Body Delineation

9:15 am **Kapoor**, S. Jerry and Albertin, Uwe, K.

9:40 am Refreshment Break and Posters

Session I—New Techniques in Modeling and Salt Body Delineation (Cont.)

Co-Chairs: P.F. Harrison and W.H. Hart

10:05 am **Ings**, Steven; Beaumont, Christopher; and Gemmer, Lykke

Session II—Diapirs and Allochthonous Salt

10:30 am **Dyson**, Ian A. and Rowan, Mark G.

10:55 am **Mohr**, Markus; Kukla, Peter A.; Urai, Janos L.; and Bresser, Georg

11:20 am **Hudec**, Michael R.

11:45 am **Dyson**, Ian A.

12:05–1:30 pm Lunch and Open Poster Booths

Session II—Diapirs and Allochthonous Salt (Cont.)

Co-Chairs: L.M. Liro and C. Hedlund

1:30 pm **Hart**, William; Jaminski, Jacek; and Albertin, Martin

1:55 pm **Liro**, Louis M.; Murillas, Joseba; Villalobos, Lorenzo; Gatenby, Glen; and Mathur, Vinod

2:20 pm **Jackson**, Martin P. A. and Hudec, Michael R.

2:45 pm **Harrison**, Holly; Kuhmichel, Lew; Heppard, Phil; Milkov, Alexei V.; Turner, Joshua C.; and Greeley, Dave

3:10 pm Refreshment Break and Posters

Session III—Extension and Inversion

Co-Chairs: D.L. Olson and M.G. Rowan

5:30–8:00 pm Hot Buffet and Poster Session (Sessions will end at 5:15)

Tuesday, December 7, 2004

Session IV—Salt, Hydrocarbons, and Brines

Co-Chairs: M.P.A. Jackson and I. Watson

9:40 am Refreshment Break and Posters

Session IV—Salt, Hydrocarbons, and Brines (Cont.)

Co-Chairs: K.T. Lyons and R. Sassen

Session V—The Role of Salt in Regional and Basin-Scale Tectonics

12:05–1:30 pm Lunch and Open Poster Booths

Session V—The Role of Salt in Regional and Basin-Scale Tectonics (Cont.)

Co-Chairs: G. Tari and M.L. Albertin

3:10 pm Refreshment Break and Posters

Session VI—Salt in Contractional Settings (Foldbelts)

Co-Chairs: P.J. Post and M.J. Roberts

Wednesday, December 8, 2004

Session VII—Shale Tectonics

Co-Chairs: S.L. Palmes and L.J. Wood

Session VII—Shale Tectonics (Cont.)

Co-Chairs: K.A. Giles and M.R. Hudec

Session VIII—Salt-Sediment Interaction

Salt Tectonics in the New Millennium: Navigating the Information Flood

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Abstract

Successful hydrocarbon exploration has produced a surge of interest in salt basins in the last 15 years. This attention, combined with advances in seismic data acquisition and processing, has revolutionized our understanding of salt tectonics. However, the wealth of information is also a glut. Conventional mechanisms for spreading knowledge through the geological community, such as papers and presentations, are woefully inadequate for handling the volume of information that now exists. It is difficult for interpreters newly assigned to salt basins to learn what they need to know, or for experienced salt interpreters to keep up with advances in the field.

One solution to this problem is to try to merge the current understanding of salt tectonics with modern information technology. We are constructing a digital atlas of salt tectonics called *The Salt Mine*. *The Salt Mine* is an HTML-based, interactive atlas of salt structures and associated sediment geometries. When complete, the atlas will contain hundreds of images of salt structures from around the world, together with captions that discuss the processes illustrated. All images are grouped into structural styles, based on a geometric classification rather than on their mode of origin, which is often contentious. Images include field exposures (outcrop views, geologic maps, aerial photographs, and satellite images), seismic sections, geologic cross sections, conceptual sketches, and animations. In addition, the atlas will showcase hundreds of the best examples from the Applied Geodynamics Laboratory's collection of physical and numerical models. Images in *The Salt Mine* can be located using five different methods: keyword search, geographic location, structural style, geometric classification tree, and a table of contents. In addition, three forms of help are available: list of references, glossary of salt tectonics, and a user's guide. The goals of this effort are to provide novices in salt tectonics with a comprehensive guide that assumes no previous knowledge and to offer more-experienced workers a ready source of analogs and alternative interpretations.

On Integrating Salt Motion in Basin Modeling: A Hybrid Approach for Goal-Oriented Salt Flow

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Abstract

In this paper, we describe techniques to calculate the internal flow from kinematic salt motions derived from palinspastic reconstructions. The calculated internal salt flow is integrated into the dynamic basin models. The internal salt flow is constrained by the imposed velocity field on the deforming boundaries, mass conservation, and the incompressibility condition during the salt deformation, yielding an optimal, physically valid, kinematic motion that achieves the goals specified by the geologist. Stokes flow physics is used to calculate the internal flow of a salt body induced by the deformation of its surface. In the numerical solution of basin models, an Arbitrarian Lagrangian-Eulerian (**ALE**) numerical scheme is used to couple the motion field and compaction. This approach has the advantage of reproducing exactly the geologist's reconstruction of the salt evolution, and the very complex salt shapes observed in the field can be simulated without the difficulties normally associated with the solution of dynamic viscous flow formulations. Therefore, this approach is an alternative to both the pure kinematic geometric reconstruction and the traditional dynamic approach.

Integrating Complementary Tools for Depth Imaging

Kapoor, S. Jerry
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Abstract

Several field examples of Kirchhoff depth imaging, tomography, and wave-field extrapolation imaging are presented. These examples illustrate how compensation for anelastic attenuation, multiple attenuation, tomography, and wave-field extrapolation can be used in a complementary fashion to provide improved interpretation and imaging in areas of significant geologic complexity.

Numerical Modeling of Salt Tectonics on Passive Continental Margins: Preliminary Assessment of the Effects of Sediment Loading, Buoyancy, Margin Tilt, and Isostasy

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Abstract

Salt tectonics in passive continental margin settings is investigated using a 2D vertical cross-sectional finite element numerical model of frictional-plastic sedimentary overburden overlying a linear viscous salt layer. We present preliminary results concerning the effects of sediment progradation over salt, buoyancy driven flow owing to density contrast between the sediment and salt, regional tilt of the salt layer, and local isostatic adjustment of the system. Sediment progradation causes a differential load on the underlying salt, which can cause the system to become unstable, leading to landward extension accommodated by seaward distal contraction. Slow progradation (V_{sp} = 0.5 cm/yr) of slightly aggrading sediments gives a diachronous evolution comprising four main phases: (1) initiation of salt channel flow and the formation of mini-basins and associated diapirs; (2) onset of listric normal growth faulting and extension of the sedimentary overburden; (3) large-scale evacuation of the salt, formation of pre-rafts and rafts, and inversion of the mini-basins; and (4) formation of a contractional allochthonous salt nappe that thrusts over the depositional limit of the salt.

Buoyancy effects are investigated using models with density contrasts between overburden and sediment of 0, 100, and 400 kg/m^3. Although the lateral flow driven by differential loading dominates in all cases, the form of the mini-basins, the overall salt evacuation, and style of diapirism are sensitive to buoyancy forces, as the large density contrast produces the most developed diapiric and mini-basin structures.

A regional seaward tilt of 0.2° (of the type that may be produced by thermal contraction of the rifted margin) enhances and accelerates the overall seaward flow of the unstable slope leading to much earlier overthrusting of the distal depositional limit of the salt. The added down-slope gravitational component also modifies the style of the mini-basins by enhancing the horizontal channel flow by comparison with the vertical buoyancy driven flow. This reduces the apparent efficiency of diapirism.

Local isostatic adjustment, owing to overburden and water loading, introduces a landward tilt of the system, thereby requiring salt to flow updip against gravity during evacuation. Isostasy also changes the overburden geometry and, therefore, modifies the stability and flow velocity of the extending overburden through the increased strength of the isostatically thickened proximal overburden, and through the modified differential pressure acting on the salt under these circumstances. The seaward flow of the unstable slope region is slower for the same overburden progradation velocity, more salt remains beneath the shelf as rollers and pillows during evacuation, counter-regional faults are more pronounced, and the allochthonous salt nappe progressively climbs above the isostatically adjusting sediments as it overthrusts.

Geology of a Welded Diapir and Flanking Mini-Basins in the Flinders Ranges of South Australia

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Abstract

The Oladdie Diapir in the southern Flinders Ranges of South Australia presents an exceptional opportunity to examine salt withdrawal and mini-basin development adjacent to diapirs. The diapir occurs on the common limb of an anticline-syncline pair in the Nackara arc of the Cambro-Ordovician Adelaide fold belt. The post-diapiric contractional tilting and subsequent unroofing have fully exposed a cross-sectional view of the diapir and the flanking mini-basins from the autochthonous evaporite layer upward for approximately 4 km. Both the autochthonous layer and the diapir comprise a caprock assemblage with a dolomitic siltstone matrix surrounding exotic rafts, including sandstone, that were depositionally interbedded with the evaporite.

The base of the diapir is a triangular pedestal rooted in the autochthonous layer. Sandstone rafts occur in recumbent folds within the pedestal and converge upward toward the pedestal apex. Higher, a steep weld associated with elongate sandstone rafts and remnant diapiric matrix connects the pedestal to a flaring diapir at the top of the exposed section. Locally, a shale sheath is preserved along the southern margin of the weld and pedestal.

During the Neoproterozoic, two salt-withdrawal mini-basins, having very different sedimentation rates and facies, formed on either side of the Oladdie Diapir. Abnormally thick, transgressive units in the southern mini-basin form a monoclinal growth wedge that dips toward the diapir and is down-dropped by over 1 km relative to the northern mini-basin. Varying development of near-diapir unconformities and debris flows show that the degree of halokinetic deformation on the two flanks also differs, suggesting variable bathymetric relief during diapir growth and mini-basin subsidence.

The geometry of the welded diapir and its asymmetric mini-basins is analogous to the counterregional-style salt systems of the northern Gulf of Mexico and other basins. Thus, the Oladdie Diapir provides a unique opportunity to study salt-sediment interaction in a setting that has, until now, been observed only on subsurface data.

New Insights to the Evolution and Mechanisms of Salt Tectonics in the Central European Basin System: An Integrated Modeling Study from Northwest Germany

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Abstract

We use an integrated approach of seismic interpretation, sedimentary and structural analysis, and reconstruction to obtain a better understanding of the basin evolution and salt tectonic mechanisms in the classic Northwest German salt basin. Our data consist of prestack depth migrated 2D lines and 3D seismic volumes, non-depth migrated seismic data, and well data. The study area, located at the southwest margin of the Central European Basin, underwent a heterogeneous evolution and a complex salt tectonic history. We propose that a gravity-gliding system in the Early to Middle Triassic caused rafting, initial salt movement, mini-basin growth at the basin margin, and salt pillow growth in the center of the basin. A second phase of salt movement was initiated by the formation of a basement graben at the beginning of middle Keuper time, triggering reactive diapirism, breakthrough, and extrusion of the salt. Subsequent downbuilding continued up to the Jurassic producing sedimentary wedges, salt flanges, and salt re-sedimentation. We suggest that the latest (reactivation) phase of salt rise by diapir shortening is due to Late Cretaceous to early Tertiary basin inversion. In comparison to the passive margin of the Gulf of Mexico basin, which is characterized by lateral progradation, the intra-continental Central European basin shows a polyphase salt tectonic evolution that occurred under different stress regimes and sedimentary environments.

Salt Intrusion: Time for a Comeback?

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Abstract

Emplacement of allochthonous salt sheets by intrusion, long rejected as a hypothesis in the Gulf of Mexico, may be an important process in the Northwest German Basin. In that area, salt from the Permian Zechstein and Rotliegend evaporites was intruded into the Triassic Röt salt during Late Cretaceous shortening, forming “salt wings” on the flanks of many salt structures.

Structural restorations of cross sections over three of these structures illustrate some of the processes involved in salt intrusion. In all cases, the presence of separate detachments on the Zechstein and Röt salts played a key role in the style of deformation during shortening. Two of the structures existed only as gentle Zechstein-cored salt anticlines prior to the Late Cretaceous. During shortening, the anticlines localized thrust faults that linked the Zechstein and Röt detachment levels. The thrusts carried Zechstein salt upward to intrude into the Röt. Sediments above the Röt salt deformed by a combination of thrusting and detachment folding, with salt from the deeper Zechstein level filling in the cores of the folds. The third structure was a salt wall prior to the Late Cretaceous. Shortening squeezed the wall nearly shut. Part of the displaced salt extruded at the surface to form a salt sheet; the rest was intruded laterally to form a wing at Röt level.

Salt wings that were emplaced into the core of detachment folds can be interpreted as passive structures that filled space during fold growth. However, this explanation does not account for salt wings emplaced on the flanks of salt walls, which may require a more active role for the salt. In either case, it appears that salt intrusion may be an important process in the formation of allochthonous sheets in basins having multiple salt layers.

Christmas Tree Diapirs and Development of Hydrocarbon Reservoirs: A Model from the Adelaide Geosyncline, South Australia

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Abstract

Christmas tree diapirs in the Adelaide "Geosyncline" of South Australia are characterized by lateral tongues of allochthonous breccia derived from an autochthonous level that contains evaporites and a caprock assemblage of blocks (or 'rafts') of non-evaporitic lithologies. These breccias may be attached to a diapiric trunk (consisting of evaporites and breccias) that may be connected to the autochthonous level. This paper describes two prime examples that outcrop at Pinda Springs and Wirrealpa Springs in the central Flinders Ranges of South Australia.

The Christmas tree diapirs evolved from an initially reactive triangular, or anvil-shaped, diapir and separate two mini-basins of different accommodation potential and often completely different sedimentary facies. An interpreted submarine salt glacier at Pinda diapir was extruded as an allochthonous salt tongue nearly 7 km long and 500 m thick. It overlies a major disconformity close to the diapir and the step-like base suggests aggradation and progradation within the transgressive systems tract. At Wirrealpa diapir, multiple tongues are contained within some 50 high-frequency sequences of the main mini-basin where deposition was influenced by the high subsidence rate, coupled with high sediment supply. The distinction is made between halokinetic sequences bounded by ravinement surfaces and the high-frequency sequences bounded by regressive surfaces of erosion. Both sequence types can be arranged into progradational, aggradational, and retrogradational stacking patterns. The model for Christmas tree diapirs, based on outcrop mapping, done as part of this study, suggests that a number of potential hydrocarbon traps can be related to different stages in the evolution of these halokinetic structures.

Recognition and Exploration Significance of Supra-Salt Stratal Carapaces

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Abstract

The term "carapace" has been informally used to describe a variety of semi-conformable supra-salt stratal packages. We propose a concise genetic and geomorphic definition and itemize the exploration benefits of carapace recognition. By specifying the term to denote condensed, sub-parallel strata originally deposited over bathymetrically raised salt domes, canopies, and sheets, we can define a genetic stratal family that is both kinematically and sedimentologically distinct from adjacent and overlying basin-fill sequences. While stratal carapaces may be displaced into varied and extreme configurations within complex Gulf of Mexico salt systems, characteristic geomorphic traits render them recognizable on seismic data sets. Perched atop allochthonous salt or remnant welds, Gulf of Mexico carapace packages range up to 5,000 feet in thickness and typically feature sub-parallel internal strata. Basal strata are semi-conformable to the underlying salt, while outer carapace boundaries may occur as lateral and vertical transitions to non-isopachous strata, or as discrete unconformity surfaces and high-angle salt cutoffs. Carapace strata often deform as semi-rigid blocks, in contrast to flexed basin-fill sequences.

Numerous commercial and technical incentives exist for identifying stratal carapaces: (**1**) they present compromised exploration targets, typically lacking extensive sand distributions and often assuming steep inclinations at mini-basin margins (**2**) they may be lithologically prone to being geopressured and can pose substantial drilling challenges; (**3**) inclined carapaces can form effective trapping surfaces for onlapping basin-fill reservoir facies; (**4**) shallow carapaces may degrade seismic resolution of underlying subsalt objectives, while certain subsalt trap styles incur the risk of containing deeper carapace strata; (**5**) semi-rigid carapace blocks enable novel restorations of bowl-shaped canopy collapse basins; and (**6**) the carapace concept augments Gulf of Mexico ponded-slope facies models.

Salt Sutures in Single- and Multi-Tiered Allochthons, Green Canyon and Walker Ridge Areas, Deep Water Gulf of Mexico

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Abstract

Improvements in 3D seismic data and depth imaging of allochthonous salt bodies in the deep water Gulf of Mexico allow for detailed definition of individual salt allochthons, and an understanding of their number and distribution.

Single-tiered allochthons represent salt originating directly from Mesozoic salt layers. The family of single-tiered allochthons defines the present-day Sigsbee Escarpment. Triangular notches along the base of the allochthonous salt surface commonly characterize single-tiered allochthons. The notches are located between demonstrable vertical salt feeder regions, and are interpreted to represent early lateral suture regions with little associated sediment deformation. Perimeter sutures are located between the tapering, leading edge of the allochthon and its impingement with an adjacent allochthon. These sutures are most pronounced where the tapering leading edge of one allochthon impinges upon the source feeder region of the second allochthon.

Multi-tiered allochthons emanate from deformed precursors at deeper levels. They are typically rugose along their top salt surface, resulting in seismic ray path distortion and the consequent loss of and/or a poor subsalt image. Multi-tiered allochthons also display abundant internal reflectors and complex suturing.

Extensive lateral sutures are observed both in single-tiered and multi-tiered salt regions. Lateral sutures, in single-tiered allochthons, are associated with salt feeder regions and parallel or diverge slightly away from the base allochthon seismic event. These sutures are located in the lower third of the amalgamated salt body, suggesting an early origin. In multi-tiered allochthons, the lateral sutures are observed at any height within the allochthon and display less affinity to vertical salt sourcing regions.

A New Mechanism for Advance of Allochthonous Salt Sheets

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Abstract

The 500-km-long Sigsbee Escarpment overlies the leading edge of a salt-canopy system in the northern Gulf of Mexico. The escarpment separates the lower slope from the abyssal plain. Bathymetric relief of the escarpment ranges from 300 to 900 m, suggesting that the canopy is still advancing although it is almost everywhere buried beneath a roof comprising hundreds of meters of Pliocene–Holocene-age sediments. Existence of such a roof means that the canopy cannot be advancing by extrusion. Interpretations of the Sigsbee salt canopy have previously drawn attention to thrusts that root into the leading edge of the salt. These thrusts are inferred to accommodate intrusive advance of the salt allochthon over the abyssal plain. Based on our interpretation of 3D pre-stack depth-migrated seismic data over a 48-km segment of the Sigsbee Escarpment, we propose accretionary advance as an additional hypothesis for salt sheet intrusion. In most of the study area, Pleistocene abyssal-plain sediments form an internally thrusted accretionary wedge in front of, and below, the leading edge of the salt canopy. As the salt and its siliciclastic roof advance, new thrusts break progressively farther out into the undeformed abyssal plain, increasing the cross-sectional area of the wedge. Because the footwall wedge contains synkinematic sediments, shortening decreases upward, so the upper reflectors of the accretionary wedge are more continuous than the lower ones. Stacking of imbricate thrusts backfolds the base of the salt sheet. By this means, salt flats can become distorted to form apparent salt ramps. The Sigsbee accretionary wedge has features in common with convergent-margin accretionary wedges, which are roughly ten times wider and advance faster. Potential geohazards are posed by the existence of currently shortening, or formerly shortened, accretionary wedges overridden by advancing salt sheets.

Base of Salt Structure and Stratigraphy—Data and Models from Pompano Field, VK 989/990, Gulf of Mexico

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Abstract

The Pompano salt canopy has been penetrated by six wells between 2001 and 2003 to test and develop various subsalt and extra-salt plays. Data from these wells provide insight into subsalt geologic models that may be applicable to other subsalt prospects in the Gulf of Mexico. The wells are aligned in a dip direction along the length of the salt canopy from the upturned section (which onlaps the flank of the salt), to beneath the salt, 5,600 feet back from the leading edge of the salt. In addition, almost the entire Miocene section has been tested below the salt. Pressure, dipmeter, and paleontological data indicate a zone about 400 feet thick below the base of salt, roughly conformable with the base of salt, and which terminates rapidly towards the leading edge of the salt canopy. These characteristic features are interpreted to be a shear or fault zone immediately below the base of salt.

The Pompano salt canopy is anomalous among salt sheets because permeable sands occur immediately beneath, and juxtaposed against, the base of salt in a zone referred to as the 'basal shear' or 'disturbed' zone. This provides a rare opportunity to measure the pore pressure within the zone, and to generate pressure profiles below the salt.

Within the high-pressured section near the base of salt, anomalous structural dips were encountered which were generally parallel to the base of salt. Migrated, thermogenic petroleum fluids having varying maturity and gas-oil ratio are found near the base of salt. Biostratigraphic data collected immediately beneath salt can indicate that the sequence is upright or overturned and consistently older than the rock found below, in addition to being fairly constant in thickness. The transition between the section adjacent to the salt and the country rock is abrupt and has all the attributes of a major fault. The section in the shear zone can be up to 1,000 feet structurally higher than the estimated cut-off on the footwall. In light of these observations, the preferred subsalt model for Pompano is a base of salt shear zone.

Map Patterns of Rafted Blocks in Outcrops and Experimental Models

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Abstract

Early evolutionary stages of salt-bearing margins (*e.g*., South Atlantic or eastern Gulf of Mexico) often include one or more episodes of raft tectonism, during which large overburden blocks, separated by normal fault zones, are translated basinward. Because boundary conditions prevailing during onset of deformation partly control the trend and spacing of normal faults, they also determine the shape of rafted blocks in map view. In addition, because boundary conditions in the downdip part of the margin determine available accommodation space into which the rafted blocks are translated, they can influence the direction of raft movement (parallel, convergent, or divergent).

The Canyonlands National Park area of Utah (Fig. 1) provided an excellent mesoscale field example of thin-skinned extension, where local boundary conditions influenced the shape and translation direction of rafted blocks. Rafting initiated when the Colorado River incised the Cutler-Hermosa formations (overburden) down to the top of the mobile, evaporitic Paradox Formation (source layer). The overburden spread gravitationally toward the river valley, forming long rafts, that moved parallel (toward the valley), and that were separated by grabens whose traces are concave toward the valley. Using physical models, we demonstrate that fault curvature results from shear stresses between the rafted area and fixed, lateral regions. In contrast, smaller areas bordering river meanders underwent divergent spreading. Ironically, valley curvature there led to formation of linear, rather than arcuate, faults arranged in two orthogonal sets.

The Wilcox Raft: An Example of Extensional Raft Tectonics in South Texas, Northwestern Onshore Gulf of Mexico

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Abstract

Examination of 2D seismic data in South Texas has identified what is now interpreted to be a large, rafted block of Eocene, Paleocene, and Cretaceous strata, analogous to rafts identified in the Kwanza Basin of Angola. Preliminarily named the "Wilcox raft" because of its association with the Wilcox depotrough, it has been identified in the subsurface extending from Starr County on the Texas–Mexican border, northward over 200 kilometers into Live Oak County, Texas. The actual extent of rafted material may extend farther to the north and/or south. The raft's detachment surface is interpreted to be at the base of the Jurassic Louann salt.

The Wilcox raft contains one primary block more than 150 kilometers long and 15 to greater than 30 kilometers wide. The primary raft block may be segmented, and the entire rafted unit may include a number of smaller branching arms, ramps, and offset fault blocks. Various portions of the raft have downdip displacements from 5 to greater than 30 kilometers. The raft is bound on the west by expanded upper Wilcox (early Eocene) strata and on the east by expanded Queen City (middle Eocene) strata. Other incompletely detached blocks lie to the west of the raft across the Wilcox depotrough. Raft geometries suggest that at least one additional rafted block lies farther basinward of the Wilcox raft, possibly beneath expanded Vicksburg (early Oligocene) strata.

A proposal for rafting in this area of South Texas is not entirely new. Earlier modeling and restorations across the Wilcox depotrough have incorporated rafts. However, these models are predicated on large-scale salt withdrawal and incorporate more than three kilometers (>10,000 feet) of autochthonous salt occupying the area of the Wilcox depotrough. We believe that a much thinner autochthonous salt layer existed beneath South Texas. In other areas of the northern Gulf of Mexico, where thick autochthonous salt existed, salt stocks are abundant. Although a few salt structures do exist in South Texas, there are very few compared with other interior salt basins. Forward modeling suggests that large sedimentary structures in the Wilcox depotrough, which can be misinterpreted as turtle structures, are related strictly to deposition during raft extension and not salt withdrawal. The geometries can be produced purely by extension on multiple detachments (Louann and lower Paleocene Midway shales) linked by ramps that dip both basinward and landward.

The Role of Halokinesis in Supra-Salt Fault Development: Insights from the North Sea

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Abstract

Seismic mapping of the salt-influenced Late Jurassic Shearwater fault system (central North Sea) has revealed that salt mobility has had fundamental control on the development of supra-salt faulting in the area. The Shearwater fault system consists of four distinct fault segments each of which increase in displacement towards a salt diapir developed in a central area where the segments intersect. The evolution of the fault system is recorded by sediment geometries in Late Jurassic syn-rift sequences, which reveal that the salt diapir and fault system evolved simultaneously with a fundamental inter-relationship between salt mobility and the evolution of the fault system. Comparisons of faulting in the Shearwater area with faults developed in the salt-free northern North Sea show that significant differences exist in the nature of fault geometries, footwall dips and fault related hanging wall depocenters. All of these variations can be attributed directly to the influence of salt mobility. Consequently, caution should be used when applying conventional models of fault development derived from salt-free settings to evaporite basins.

Basement vs. Salt Tectonics and Salt-Sediment Interaction—Case Study of the Mesozoic Evolution of the Intracontinental Mid-Polish Trough

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Abstract

The Permian to Cretaceous Mid-Polish Trough belonged to the system of epicontinental depositional basins of western and central Europe and was filled by several kilometers of siliciclastics and carbonates, including thick Zechstein (approximately Upper Permian) evaporites. The Mid-Polish Trough was inverted in Late Cretaceous–Palaeocene times, when its axial region was strongly uplifted and eroded. The presence of thick salt significantly influenced Mesozoic basin extension and inversion. Extensive seismic data is available which, in conjunction with deep research and exploration wells, enabled the construction of detailed tectono-stratigraphic models of the relationships between basement and cover tectonics as well as the interaction between salt structures and surrounding depositional systems. The apparent lack of major extensional deformation within the post-salt Mesozoic infill is responsible for several pulses of tectonic subsidence. These have been inferred from tectonic modelling studies and are attributed to the basin-scale mechanical decoupling between the sub-salt (sub-Zechstein) basement and the post-salt Mesozoic sedimentary infill. During such decoupled evolution, major faulting was primarily restricted to the basement, and only secondary faults and associated peripheral deformations developed within the post-salt sedimentary cover. In the central Mid-Polish Trough, because of strong basement extension, salt diapirs that partly extruded onto the basin floor formed. The surrounding Triassic and Jurassic depositional systems were strongly influenced by the combined effect of salt pillow/diapir rise and basement extension. Detailed seismostratigraphic analysis of the cover patterns indicates the timing of major extensional and compressional events and related formation of salt structures. Results of seismic data interpretation conform very well with published results of analog modeling.

Regional Assessment of Salt Weld Timing, Campos Basin, Brazil

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Abstract

Pre-salt (Aptian) lacustrine shales are the primary source rocks that charge late Cretaceous and Tertiary reservoirs in the petroliferous (15 billion barrels of oil recoverable) Campos Basin. As a result, an understanding of salt weld timing is a critical component in assessing charge risk and high-grading deep-water play fairways. The traditional method of assessing regional structural timing with isochron maps, although useful, often yields erroneous results when weld timing is being ascertained. Mini-basins that have welded and display onlap stratal geometry at their margins may have the same isochron map pattern as actively subsiding basins which have growth wedge stratal architecture. Utilizing a regional grid of 2D seismic lines, we have developed a methodology which identifies salt weld timing by classifying the stratal geometries of third order sequences within welded mini-basins. These seismic facies accurately map the evolution of weld timing within each Campos mini-basin. A basin-wide "weld timing" map has been constructed and compared to regional sedimentation patterns and hydrocarbon charge modeling. At the local scale, the growth of individual welds can be compared with mini-basin structural geometries through time to assess drainage potential. We find that salt weld timing is positively correlated with regional sediment isopach thickening but true weld timing and mini-basin evolution can only be understood by systematically mapping stratal architecture. Understanding salt weld timing has profound implications on basin modeling and future exploration risk assessment within the Campos and similar basins.

Do Salt Welds Seal?

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Abstract

An important question in the exploration of salt basins is whether or not salt welds can seal hydrocarbons in subweld traps. Any answer must start with the observation that many supraweld traps throughout the world are charged with hydrocarbons from subweld source rocks, requiring migration through welds. However, not all welds are the same, and this conceptual paper examines various factors that may influence the sealing capacity of salt welds. The probability of weld seal is enhanced by: (1) the presence of remnant evaporite along the weld; (2) relatively impermeable lithologies across the weld; (3) subweld reservoirs that are encased in shales rather than in contact with the weld; (4) the presence of clay gouge or smear generated during faulting; and (5) an original base-salt geometry that creates divergent subsalt hydrocarbon migration pathways. Another factor that must be considered is the timing of overburden deformation with respect to that of hydrocarbon generation and migration.

Although weld seal is certainly a risk, traps that invoke weld seal should not be summarily discarded. Instead, each prospect should be evaluated separately in light of the factors presented here in order to derive a better assessment of the inherent risk. In addition, the ideas presented here need to be tested with observations obtained from surface exposures and a combination of subsurface well and seismic data.

Hydrocarbon Migration and Accumulation Above Salt Domes—Risking of Prospects by the Use of Gas Chimneys

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Abstract

In many cases, seismic data show indications of shallow gas accumulations above salt domes. Faults created by the upward movement of the salt are believed to act as hydrocarbon migration pathways. This involves a risk of leakage from the deeper reservoirs. Gas chimneys may provide additional indications on the risk of leakage of hydrocarbons from deeper reservoirs.

To enable the mapping of gas chimneys in a consistent manner, a method for the detection of chimneys in post-stack 3D seismic data has been developed. This recently developed method makes use of multiple seismic attributes and neural network technology. The output, after chimney detection, is a 3D cube in which high values have been assigned to samples inside chimneys and low values to the background, and from which the shape and the spatial distribution of the chimneys can easily be visualized.

Gas chimneys have been observed above hydrocarbon-charged, as well as dry structures. However, the way chimneys appear in the two cases seems to be different. Chimneys above dry structures coincide with faults across the top of the structures. Chimneys above hydrocarbon-charged structures are observed over a wide area above each structure and are not coincident with a fault.

Geopressure Compartmentalization in Salt Basins: Their Assessment for Hydrocarbon Entrapments in the Gulf of Mexico

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Abstract

The complex interaction between salt and surrounding sediments makes risk assessment of a prospect or play concept a challenge. Geopressure compartmentalization in the Gulf of Mexico Tertiary-Quaternary salt basins is created mainly by the principle stresses resulting from interaction between the sediment load and tectonic movement of salt.

The unique petrophysical properties of salt contribute to changes in the structural setting and affect the sealing capacity and hydrocarbon retention capability of traps. The low density of salt may retard the sealing capacity in subsalt sediments, while enhancing the seal capacity in supra-salt sediments. Because salt is relatively impermeable, its contact with surrounding sediments forms a barrier to hydrocarbon movement. The integrity of the sealing interface is usually impacted by the salt tectonic history.

The ductile nature of salt creates different forms of salt tectonics, such as diapirs, ridges, salt withdrawal basins, overhangs, canopies, *etc*., that have a direct impact on stress orientation.

Establishing the predicted pore pressure in the impermeable beds (shale) compared to the measured pressure in the reservoir facies (sands), plays an important role in assessing the entrapment and sealing capacity of traps. In this study, wells are analyzed from several different salt tectonic settings in the Garden Banks, Mississippi Canyon, and Green Canyon protraction areas (Fig. 1). While a great deal is known about salt body delineation from geological and geophysical data, this paper addresses salt-related hydrocarbon traps from a geopressure standpoint.

Brine Vents on the Gulf of Mexico Slope: Hydrocarbons, Carbonate-Barite-Uranium Mineralization, Red Beds, and Life in an Extreme Environment

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Abstract

Enormous volumes of middle Jurassic Louann salt dissolve during migration of fluids from depth. At the seafloor, the result is vents, pools, and down-slope flows of brine. At these locations, biogenic methane or C_1-C_5 thermogenic gases are present in high concentrations. New $\Delta^{14}C$ measurements indicate a deep fossil source of this biogenic methane. However, gas hydrate is not found at brine sites because high salinity retards the crystallization process. Microbial hydrocarbon oxidation and sulfate reduction occur in brine and associated sediment that drives massive precipitation of authigenic carbonate rock depleted in ^{13}C. The authigenic carbonate rock is often radioactive and has diagnostic barite-uranium mineralization.

Thick red beds occur as a consequence of mobilization of iron from the subsurface by brines. The flow of these brines over shallow, or exposed, salt in Walker Ridge in a water depth of 2,037 m has deposited red iron hydroxide layers up to 4.6 m thick. Iron comprises 24.1-24.6% of the sediment. Hematite, dolomite crystals, and uranium minerals are minor components of the red beds.

Methane-rich brines favor simple chemosynthetic communities of methane-oxidizing mussels and sulfide-oxidizing bacterial mats, decreasing biologic diversity relative to nearby chemosynthetic communities not affected by brines. Crude oil is altered by microbial oxidation, concentrating toxic aromatic hydrocarbons in the brine environment along with uranium, radium, and toxic metals. Consequently, brine-related chemosynthetic communities appear to exist in the most extreme environment for life on the seafloor of the Gulf of Mexico slope. The characteristics of hydrocarbon-charged brine expulsion features are likely to be preserved during deep burial, allowing dating of major phases of hydrocarbon migration in the geologic past.

The Role of Salt Dissolution in the Geologic, Hydrologic, and Diagenetic Evolution of the Northern Gulf of Mexico Sedimentary Basin

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Abstract

Formation waters of the northern Gulf of Mexico sedimentary basin (Gulf of Mexico) typically have salinities significantly in excess of the fresh, brackish, or normal marine salinities that characterized the original depositional environments of most of the sediments in the basin. Although some of the excess salinity has been inherited from brines formed by subaerial evaporation, much is the result of the subsurface dissolution of halite. Subsurface dissolution has played an important role in the geologic, hydrologic, and diagenetic evolution of the Gulf of Mexico. Salt dissolution has reduced the volume of solid salt in the Gulf of Mexico and may be a factor accounting for missing salt in large-scale reconstructions of the tectonic history of the Louisiana continental shelf and slope. Locally, loss of a cubic km, or more, of salt has been documented for some individual salt structures.

The formation of saline brines along with the high thermal conductivity of salt produces lateral and vertical fluid density differences that have the capacity for generating vigorous fluid circulation around salt structures and for long-distance fluid migration. Some of this density-driven fluid flow could be responsible for water-washing of hydrocarbons. On a regional scale, thermohaline circulation has effectively decoupled the regional meteoric and overpressured flow regimes in many areas of the onshore and coastal Gulf of Mexico. Spatial differences in formation water salinity have proven useful in delineating reservoir continuity and compartmentalization.

A large body of published analyses for Gulf of Mexico formation waters shows that as brines derived from the dissolution of halite begin to evolve diagenetically, there is loss of dissolved Na and a gain in dissolved K, Mg, Ca, and Sr as the fluids attempt to equilibrate with ambient silicate and carbonate mineral phases. The attainment of fluid-mineral equilibration has the potential for creating secondary porosity and precipitating cements.

A Comparison of Salt Tectonic Subprovinces Beneath the Scotian Slope and Laurentian Fan

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Abstract

A surge of exploration activity along the continental slopes offshore of Nova Scotia and Newfoundland has generated significant advances in the understanding of the salt tectonics beneath these regions. Although well control beyond the shelf break is still sparse, extensive coverage by modern 2D seismic data permits definition of five tectono-stratigraphic subprovinces, each with a distinctive salt deformation style related to regional basement morphology and first-order differences in sedimentation. The deformation styles range from halokinetic growth of passive diapirs sourced from a primary salt basin to extensive development of allochthonous canopies seaward of rapid progradation. Thin-skinned extensional and contractional structures are evident throughout the study area.

A Comparison Between the Salt Basins of the Gulf of Mexico and the South Atlantic

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Abstract

Two of the major petroleum-bearing salt basins located on divergent margins are the Gulf of Mexico and the South Atlantic. Even though investigations have been going on for 'decades,' exploration is still very active, focusing particularly on deep-water Tertiary turbidite plays.

The geodynamic evolution of these margins controls the key parameters of salt tectonic evolution from the earliest stages in Jurassic-Cretaceous times to the present-day.

Some of the key parameters are compared and discussed as they relate to the regional geodynamic context:

- the size and shape of the initial, reconstructed, salt basins before the initiation of seafloor spreading, including the presence of one or more sub-basins and their impact on the continuity of the salt décollement layer;
- the differences in the initial salt thickness and its impact on later ductile deformation;
- the control of the geometry of the basement; *e.g.*, ramp and flat, horst, *etc*. on salt tectonic zonations and deformation;
- the polyphase timing of the salt tectonics; *i.e.*, changes in the regional sliding/slope between early and late deformations.

We conclude that the understanding of the regional evolution of these basins is the key to understanding their salt tectonic evolution, which controls the primary parameters of petroleum systems.

Salt Tectonic Domains and Structural Provinces: Analogies Between the South Atlantic and the Gulf of Mexico

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Abstract

Industry, regional deep-resolution seismic reflection profiles along the shallow to ultra-deepwater regions of the South Atlantic sedimentary basins allow the interpretation of different salt tectonic compartments for the whole Aptian basin, which extends from the rift border towards the oceanic crustal limit. Geological and geophysical interpretation, particularly along regional seismic transects in the eastern Brazilian and western African margins, reveals six major salt tectonic provinces associated with gravitational sliding and spreading.

These tectonic provinces are characterized by particular salt families that have counterpart structural elements in the Gulf of Mexico, which shows better development of Jurassic salt basins onland and much thicker clastic input offshore in the Late Tertiary. The tectonic domains in the offshore region (platform and in deep waters) are characterized by halokinetic structures that developed huge salt diapirs, an extensional province associated with turtle structures, roll-overs and evacuation grabens, and particularly, by major development of allochthonous salt tongues.

Extensional elements predominate in the proximal and intermediate provinces, whereas compressional features characterize basinward provinces near the continental—oceanic crustal boundary. Volcanic features, igneous intrusions, and wedges of seaward-dipping reflectors characterize the transition from rifted continental to oceanic crust. The deep-resolution seismic profiles also allow the identification of autochthonous and allochthonous salt structures near the crustal boundary, forming bathymetric escarpments and salt nappes that extend towards the undeformed post-salt sedimentary sequences overlying oceanic crust.

Physical modelling experiments and seismic restoration using balancing techniques can constrain the seismic interpretation. We also propose conceptual plays that have not been tested in the South Atlantic but have been proved elsewhere, both in the Gulf of Mexico and in the North Sea.

Salt Tectonics of the Continent-Ocean Transition, Deep-Water Angola

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Abstract

The Late Cretaceous to present salt-cored fold and thrust belt at the edge of the Aptian salt basin, offshore Angola, has been interpreted based on seismic and potential field data. Tectonic processes, kinematic steps, and deformation styles are discussed and demonstrated using a series of regional cross sections and restorations. Based on salt tectonic deformation style, the study area has been divided into a northern fold belt and a southern fold and thrust belt. Shortening along the measured section in the northern fold belt is on the order of a few kilometers. In contrast, structural restoration demonstrates that to the south, in the fold and thrust belt, up to 12 km of compressional strain has been absorbed by the Tertiary section.

Salt occurs at three levels in the frontal deformation zone. At the deepest level, autochthonous salt pinches out against an outer high of oceanic basement at the western edge of the Angola salt basin. The second level comprises a deeply buried, regional salt canopy, located at the leading edge of the salt province in the northern part of the study area, which formed as a salt glacier during the Late Cretaceous. Large-scale, compressional, salt-cored anticlines and active diapir complexes have developed above this Cretaceous canopy, and landward, above an inflated salt pillow in Tertiary to present times. In the southern part of the study area, outboard of the Oligo-Miocene Congo Fan depocenter, and a zone of maximum extension, large-scale, salt-cored folds and thrusts developed above interpreted oceanic crust. The third, and shallowest, level of salt is organized into a middle to late Miocene canopy belt, observed just inboard of the frontal structures.

In the northern fold and the southern fold and thrust belts large-scale structures initiated in the early Tertiary and have continued to develop gradually. Large anticlines developed by downbuilding; *i.e.*, by salt injection into the fold core and contemporaneous salt withdrawal from the adjacent synclines. Folding and thrusting have been continuous up to the present, indicating a slow, but steady, deformation of the leading edge of the salt province, offshore Angola.

Salt Tectonics and Sedimentation in the Offshore Majunga Basin, Madagascar

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Abstract

The offshore Majunga basin of Madagascar appears to be the largest salt basin in East Africa. It is the previously very poorly known deep-water part of the Majunga that hosts a variety of salt features, including both autochthonous and allochthonous structures which include toe-thrust anticlines, falling and rising diapirs, turtle structures, salt tongues/canopies and withdrawal mini-basins beneath the slope. In the middle of the salt basin, the salt edge displays a major basinward salient where the Early Jurassic syn-rift salt ramped up through the Jurassic and Cretaceous strata forming a broad allochthonous salt nappe.

As only 2D seismic reflection data are available over the Majunga salt basin, it provides only a sub-regional scale example of the interaction between salt and sediments. One of the regional-scale aspects of salt/sediment interaction includes the relative importance of updip sediment loading versus regional tilting of the margin in the initiation of allochthonous salt tectonics. The uplift in the hinterland of the Majunga basin occurs during the mid-Cretaceous when the Seychelles/Indian continent rifted away from the eastern side of Madagascar. It is suggested here that it was the regional basinward tilt that triggered the salt tectonics. Thus, the subsequent Late Cretaceous, accelerated sedimentary influx only has enhanced the ongoing salt deformation.

Salt Deformation, Magmatism, and Hydrocarbon Prospectivity in the Espirito Santo Basin, Offshore Brazil

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Abstract

A combination of 3D pre-stack and post-stack time-migrated seismic data was used to examine salt structures, stratigraphy, and hydrocarbon potential in the BES 2, 100, 200 and BMES 1, 2, and 9 blocks of the Espirito Santo Basin, Brazil. Salt structures display a proximal to distal basinward transition from salt rollers, to vertical diapirs, to diapirs with overhangs and allochthonous tongues, and finally to salt canopies. The original autochthonous salt thickness increases following a similar proximal to distal basinward gradient.

Deformation, driven by a combination of gravity gliding and gravity spreading, has been a relatively continuous process in the Espirito Santo Basin. Contraction began early in the Albian and continued unabated up to the present-day. However, individual structures ceased movement at different times depending on geometry, salt supply, and overburden thickness.

A major thermal pulse affected the basin in the early to middle Eocene, associated with emplacement of the volcanic Abrolhos Plateau. Both intrusive magmas and extrusive flows are interpreted to exist. Intrusive dikes and sills display characteristic saucer shapes in cross section, elliptical to circular shapes on time slices, and cone shapes in 3D. Magmas appear to have used existing salt structures and associated fault planes as preferred pathways to reach shallower levels. Extrusive flows were identified only where seismic character, clear stratal relationships, and direct ties to intrusive geometries allowed.

All the elements for excellent hydrocarbon potential exist in the Espirito Santo Basin. The main Syn-rift II source bed found in the Campos Basin exists across the basin. Several other less documented source intervals also exist. Numerous contractional folds, turtle structures, and diapir-flank traps are present. Reservoir intervals exist in Albian carbonates, Upper Cretaceous transgressive sands, and Cenozoic regressive sands. At least one deepwater hydrocarbon system is operating, as evidenced by numerous shallow bright spots, gas chimneys, and a recent major deep-water discovery. The presence of intrusive magmas may adversely affect deeper source intervals in some places, but could locally bring immature source rocks into the oil window.

Salt Evolution as a Control on Structural and Stratigraphic Systems: Northern Paradox Foreland Basin, Southeast Utah, USA

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Abstract

The Paradox Basin is an asymmetric foreland basin, developed along the southwestern flank of the Uncompahgre uplift in southeast Utah and southwest Colorado, USA. This large basin (265km by 190km) developed during the middle Pennsylvanian-Permian ancestral Rocky Mountain orogenic event. Salt structures in the northern Paradox Basin form a variety of structural styles ranging from deeply buried salt pillows to complexly faulted diapirs and salt walls exposed at the surface. Complex intra-formational unconformities and rapid lateral stratigraphic facies variations indicate that salt structures were active over at least 75 Ma.

Analysis of field exposures, sub-surface well, and 2D seismic data across the northern part of the basin reveals a complex relationship between crustal shortening, loading, creation of accommodation space, differential sedimentation, and salt movement. Salt flow through time across the northern part of the basin reflects the varying basin geometry and its response to sediment depositional systems. From the early stages of salt movement in the upper Pennsylvanian, through passive growth of a series of large (up to 4 km high) salt walls, the dynamics of salt movement were a strong control on both structural development and stratigraphic facies architecture.

Compressional Salt Tectonics: Processes and Pitfalls

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Abstract

Salt deposited over rift sequences along passive margins flows basinward in response to thermal subsidence and non-uniform sediment loading. The flow results in extensional tectonics in the salt and the overlying sediments where the space is not constrained and in compressional tectonics where it is constrained. Salt waves form as compression propagates inward from the borders of the laterally contracting body. Upslope flow of the salt is particularly effective in creating folds having regular wavelength because of the increasing resistance. Improved seismic resolution permits recognizing the complex internal structure of the folds, whereas isolated 2D sections may be misleading. The resulting salt waves easily can be mistaken for diapirs in the conventional sense; their flanks may appear discordant when, in fact, they are not. Alternating materials of different rheological properties greatly enhance the formation of uniformly spaced waves or folds. Apart from the dominant halite, the alternating material may consist of mostly mono- or polymineralic evaporite rocks such as anhydrite, carnallite, bischoffite, or tachyhydrite, as well as alternating shale and sandstone/siltstone layers interlayered with, or overlying, the evaporites. Syndeformational sedimentation over the evaporites results in the formation of minibasins. The layers overlying the evaporites participate in the folding, with upward decreasing amplitude, so that definition of the upper boundary of the evaporite sequence on seismic sections is not always straightforward. Seismic lines from Brazil's Atlantic margin are used to illustrate these points.

Modes of Contractional Salt Tectonics in Angola Block 33, Lower Congo Basin, West Africa

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Abstract

The Lower Congo Basin is a gravitationally-driven, linked extensional/contractional system, detaching on Aptian salt, in which updip extension is compensated by downdip contraction and lateral flow of salt. Two spatially and temporally distinct phases of deformation are recognized in the Lower Congo Basin, one of Cretaceous age, and one of Oligocene to Recent age. Angola Block 33 is a deep-water block lying entirely within the contractional domain of the Tertiary system. Recently acquired 3D seismic data provide new insights into the structural evolution of contractional salt structures.

Several distinct structural domains are recognized on Block 33. (**1**) The northeastern portion of the block is dominated by turtle anticlines, the principal structural features in the Turtle Domain. (**2**) The Eastern Domain covers most of the eastern portion of Block 33, and is dominated by relatively simple, salt-cored folds associated with local subsidiary thrust faults. North-northwest- to northwest-trending salt walls are the predominant salt structures in the Turtle and Eastern domains. (**3**) The Western Domain, in contrast to the relatively simple features in the eastern part of Block 33, is structurally complex, and exhibits a variety of features, including salt stocks, salt sheets, salt-cored anticlines, and thrust faults. Thrust faults occur in a variety of orientations, commonly emanating from, and sometimes linking salt ascension zones.

Our analysis indicates that structures in Block 33 evolved in two phases: (**1**) an Aptian to early(?) Oligocene phase that lead to the formation of turtles, diapirs, and salt pillows; and (**2**) a mid(?)-Oligocene to Recent phase of contraction. Because contraction was superimposed on a pre-existing system of salt structures, mid(?) Oligocene to Recent folds and thrust faults are strongly controlled by the geometry and orientation of older structures. Stratal patterns indicate that early-formed diapirs evolved into salt glaciers at the onset of contraction, and that contraction was locally accommodated by lateral displacement of salt.

Insights from a Gravity-Driven Linked System in Deep-Water Lower Congo Basin, Gabon

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Abstract

Deep-water structures in southern Gabon are among the best imaged in the world. Our 30-km-long study area in the Anton Marin–Astrid Marin blocks runs obliquely through the northern part of the Congo Fan. The study area is entirely covered by high-quality 3D seismic data. It spans the complex transition between the landward extensional domain and the basinward contractional domain. Both domains detach on Aptian salt. We use seismic sections and dip-corrected isochron maps to illustrate and analyze the following processes.

Control of thrust location by precursor anticlines and diapirs: a regular wavelength of the early Albian gentle precursor anticlines nucleated linear, regularly spaced thrust faults; the location of precursor passive diapirs caused some thrust faults to curve to intersect with the diapirs, linking them into the overall contractional network, which includes lateral transfer zones.

Thrusting that verged consistently seaward: most other salt-based thrust belts have less systematic vergence; we attribute the consistent vergence to the high frictional resistance of the salt detachment because it had been thinned by expulsion of salt into diapirs before thrusting began.

Landward propagation of thrusting: during the late Cretaceous and Paleogene, thrusting propagated updip through the formerly translational domain because of the buttressing effect of older thrusts downdip of the study area. In the study area, distal thrusts and diapirs were still shortening while more proximal thrusts began shortening.

Extrusion of salt sheets under compression: as thrusting culminated, the precursor passive diapirs were compressed to extrude salt; extrusion continued until the diapirs were finally squeezed shut, more or less coevally across the thrust belt in the study area.

Inversion of extensional salt structures: by the Oligo-Miocene, the thrust belt had propagated landward into the formerly extensional domain; thus, diapirs and turtle structures were squeezed, old normal faults were inverted as thrusts, new normal faults formed orthogonally to older normal faults, and strike-slip faults linked older structures. The variable strikes of the old extensional or halokinetic structures caused the strike of the inversion structures to be equally variable.

Salt Movement, Tectonic Events, and Structural Style in the Central Zagros Fold and Thrust Belt (Iran)

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Abstract

Structural analysis of surface and subsurface data in the Dezful Embayment, the northern Fars, and the High Zagros provinces shows that the presence of the Eocambrian Hormuz and the Miocene Gasharan salt layers have a direct control on the structural style. Both are levels of major disharmony and decollement during the Neogene Zagros folding.

There is some evidence that Hormuz salt doming started before the Neogene Zagros orogeny. Permo-Triassic Tethysian rifting along High Zagros northwest-southeast trends and Cretaceous-Paleogene obduction and compressive events associated with basement reactivation of north-south Arabian trends could have initiated some episodic salt diapir activity in the Central Zagros province. However, in the absence of high-quality, deep seismic imaging in most of the Zagros fold zone, early Paleozoic or Hercynian salt movements are not excluded.

The Hormuz complex is known from emergent halite and anhydrite plugs in the Fars and High Zagros areas. The emergence of Hormuz evaporite plugs is closely associated with major thrusts parallel to the fold trend, such as the Dinar thrust. Plugs also occur along tear faults or where space is created by pull-apart along the north-south trending strike-slip faults. These faults and the associated salt plugs are clearly related to the Zagros folding event, even if they are sometimes located above reactivated paleo-structures. The analysis of the deformation of sandbox models using X-ray tomography suggests that the initiation of thrust and wrench faults is influenced by pre-existing salt domes (weak zones). The driving mechanism of Hormuz halokinesis and extrusion was the squeezing of pre-existing salt domes. Local pull-apart and wrench fault deflection probably also allowed for rapid rising of the evaporites.

In the Fars and High Zagros areas, the Hormuz salt series played the role of a low friction, basal décollement level, and influenced fold style by free development of fore-thrusts and back-thrusts without any preferred vergence. The high competency contrasts within the sedimentary pile favored the development of "fish tail" structures and caused axial shifting of anticlinal crests from surface to depth.

The Neogene sedimentary sequence begins with the deposition of the evaporitic Gachsaran Formation above the Asmari limestone reservoir. The lateral extent of this facies is restricted to the Dezful zone, marking the evolution of the area towards a fold belt and its associated flexural basin. Thickness variations and early diapirism show that this syntectonic deposit is contemporaneous with folding in this area. The Gasharan salt is a major level of décollement and disharmony in the north Dezful Embayment zone, south of the Mountain Front Fault. This interpretation implies that the surface expression of the structures does not reflect their geometry at depth. The Gachsaran evaporitic sequence also plays an important role in sealing Asmari reservoirs.

Shale-Detached Deformation along the Texas Shelf: 3D Analyses, Recognition Criteria, and Development of Duplex Structures in Extensional Settings

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Abstract

Detailed interpretations of 3D seismic data volumes and analyses of derivative 2D kinematic models reveal complex stratigraphic and structural relationships that are interpreted as forming duplex structures within extensional settings. These structures develop along the Texas shelf in settings containing multiple listric detachment faults soling at multiple levels. Laterally and vertically, the faults intersect and coalesce with one another in both map and cross-sectional view. Younger, landward growth faults may detach at deeper structural levels and can result in older, basinward detachment faults being folded into hanging wall structures.

Conversely, younger detachments may sole into older detachment zones deforming the older fault and overlying strata, forming hanging wall anticlines containing single, or multiple, folded faults. The resulting structures can be termed "horses" or duplexes. Two dimensional, forward modeling of observed fault geometries illustrates the structural development of extensional duplexes in dip orientation, commonly resulting in individual horses bounded by roof and floor faults. In more complex settings, individual horses may be excised, resulting in laterally and vertically stacked duplexes.

This paper documents the existence of extensional duplexes along the Texas shelf, provides criteria for their recognition in strike, dip, and map view, presents kinematic models for their structural development, discusses the internal architecture of duplexes, and identifies processes for the formation of the following structural features: horses, conformable chaotic zones, excised horses, and antiformal stacks. A full understanding of the evolution of extensional duplexes may help to assess trap, charge, sand, and reservoir risk. Applying this model to the structural evolution of the Texas shelf may provide insights into the structural style and deformational history of structures associated with, and underlying, fault systems such as the Corsair and Clemente-Tomas.

Shale Tectonism in the Northern Port Isabel Fold Belt

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Abstract

The northern extension of the Port Isabel Fold Belt is a structurally complex, linked fault system that has been significantly impacted by regional salt tectonism and shallow shale diapirism. Large-scale capture of Miocene deposition updip of an Oligocene-age extensional zone, concurrent with evacuation of salt and ductile shale, has resulted in structural inversion and overprinting phases of deformation. The structural style of this zone is characterized by an updip trend of deep Miocene basins flanked by downdip large-scale rollover anticlines. Frio sediment-cored rollover anticlines are fringed on the downdip edges by thrusts, shale diapirs, or detachment folds. Inversion within this zone is expressed by faults having sense-of-motion reversal, rollover anticlines associated with basinward vergent thrusts, pop-up structures, and shearing of large portions of the section.

The Anahuac shale is an important detachment zone within the trend and is diapiric over much of the northern Port Isabel Fold Belt. The unit is very well imaged because of its shallow position in the section and the high quality seismic data available over the area, and thereby provides a rare opportunity to view the internal deformation of ductile diapiric shale. The shale displays many characteristics similar to the deformation style of salt including mini-basin formation during early deposition, reactive diapirism of the shale layer triggered by regional extension, shale-cored detachment fold formation, and contractional diapirism, as well as more unique characteristics such as close juxtaposition of brittle and ductile behavior. The ductility of the Anahuac shale at shallow depth is unique in that it is not caused by overpressure, as is assumed of most diapiric shales.

Distribution, Nature and Origin of Mobile Mud Features Offshore Trinidad

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Abstract

The formation of submarine mud volcanoes by seafloor expulsion of deeply buried fine-grained sediments, liquids, and gases into the water column controls deep-marine topography, sediment pathways, and biota distribution in eastern Trinidad. We use approximately 8,000 km^2 of 3D seismic data in water depths of -100 to -1,450 m to study the morphology of over 161 mud volcanoes present in the study area. A variety of morphologic features associated with mud intrusion are visible on, and well beneath, the seafloor and include hydrogeologically active mud ridges, cones, and mounds, as well as inactive buried mud volcanoes and collapse features. Surface expressions of these features vary from 30m-deep sub-seafloor depressions to 150-m high cones, average slopes range from <1° to 36°, and individual volcano deposits can cover areas of as much as 10.5 km^2. The mud volcanoes of the study area belong to three different provinces: (**1**) a fault-focused province, (**2**) a mud ridge province, or (**3**) a basin-fill province. These mud volcano provinces are identified by variations in surface and subsurface mud intrusion morphology, past eruptive flows, influence of nearby faulting, and the depth of the mud mass feeding the mud volcano. In addition to the seismic data, 20 dropcores sampling 1 meter of surface sediments above the extrusive mud features have been obtained. These cores contain angular lithic clasts and reworked fauna and flora that originate from deeply buried strata. The presence of authigenic carbonates, abundant shell fragments, preserved burrows, and replaced tubeworms indicate a dense distribution of cold seep biota live in association with the fluids and gases that are emitted from mud volcanoes.

Processes of Mud Volcanism and Shale Mobilization: A Structural, Thermal and Geochemical Approach in the Barbados-Trinidad Compressional System

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Abstract

This paper illustrates the diversity of subsurface sediment mobilization features in tectonically mobile regions in a shale-rich environment. In the studied area of the southeastern Caribbean, new geophysical acquisition in Trinidad and Barbados spectacularly show the widespread development of mud volcanoes and massive sedimentary extrusions in the interference area between the southern part of the Barbados prism and the active turbidite system of the Orinoco. Mud volcanoes are well developed along ramp anticlines, or on top of sigmoid rises, which are oblique with respect to the trends of the main folds of the accretionary wedge. The area also exhibits trends of structures corresponding to massive extrusions of well preserved turbidite and hemipelagic sediments that cut the surrounding sediments. Some of these extrusion structures are complicated by the development of collapse structures, calderas, and superimposed mud volcanoes. On some active mud volcanoes, heat flow measurements show high positive anomalies and bottom simulating reflectors that are shallower compared to the surrounding areas and show high fluxes of fluid expulsion. The mobilized sediments expelled by the mud volcanoes are liquefied argillaceous and sandy material from deep horizons, and various shallower formations pierced by the mud conduits. Both in the Barbados prism and in Trinidad, the mud expelled is rich in thin, angular, and mechanically damaged quartz grains related to shearing and/or hydraulic fracturing processes. The exotic clasts and breccia result mostly from hydraulic fracturing. In Trinidad, the gas phase is mainly deep thermogenic methane associated with hydrocarbon generation at depth.

This paper emphasizes that subsurface, clay-rich formation mobilization notably differs from salt mobilization by the role taken by the fluid dynamics that control overpressured shale mobilization, and induce sediment liquefaction. Mud volcanism corresponds to fluid displacement, whereas massive sedimentary extrusion corresponds to large movements of stratified solid levels for which the deep cause could be the intrusion of mud plugs. Both are dynamic phenomena controlled by the development of overpressure at depth, contributing to sediment mobilization by reducing the strength within the overpressured layer. The regime of the expulsion of the fluids varies according to cyclic phases. Low-frequency cycles, notably the catastrophic events, are controlled by the dynamic development of overpressure. They could be related to the fact that when high excess pore pressure occurs at depth, hydraulic fracturing is responsible for opening the fracture network favoring successive fluid release and cyclic pressure decrease. Such processes could be enhanced by a threshold effect when fluids are oversaturated in gas. In that case, massive degassing of a large volume of dissolved gas at depth is possible, resulting in a sudden rise in fluid pressure and damage to the sealing properties of the sediments above gas-charged mud chambers.

Influence of Mobile Shales in the Creation of Successful Hydrocarbon Basins

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Abstract

Shale mobilization (argillokinesis) is an important process in several major worldwide hydrocarbon basins and in most cases is critical to their prospectivity. The southern Gulf of Mexico, Niger offshore, Caspian Sea, northeastern Venezuela and Trinidad, Indonesia, and the Mackenzie Delta of northern Canada are all excellent examples of these argillokinetic basin types, where the effects and prospects associated with mobile shale systems can be examined in detail. Unlike salt, which will move and maintain movement under very limited impulses, shale requires overpressure to become ductile. Shale may move from ductile, to plastic, to fluidized, and back to ductile, numerous times throughout its active life. Overpressure is typically caused through some combination of burial compaction, diagenesis of clays, kerogen maturation, and compressive tectonics. Shale's tendency toward pulses of inflation and deflation results in dynamic states of erosion, accumulation, and explosion associated with mud volcanoes. The active fluid migration necessary to maintain these episodes forms vents for hydrocarbon migration from sometimes deeply buried source rocks to shallower reservoirs and traps, setting up the perfect prospective scenario. Traps associated with shale diapirs include detachment folding, diapir toplap, diapir top drape or rollover rims, radial faults, tilted fault blocks, erosional truncation and associated unconformity traps, lateral mini-anticlines, and down-built anticlinal flank traps.

Mobile shales are an important component of the overall history of evolution in the Columbus and offshore Orinoco sub-basins of the eastern East Maturin Basin, offshore northeastern South America. The area is located on the southeastern front of the modern day Barbados accretionary prism. It is an area of active transpressive tectonics, large-scale growth faulting, and enormous sedimentation from the Orinoco Delta.

Detachment growth folding is a prominent feature in the shelf strata. Mobile shale features in these more proximal regions include shale walls, welds and rollers. Large bi-directional and mono-directional roll-over anticlines form the major hydrocarbon fields in association with listric growth faults formed by gravity gliding over a deeply buried shale detachment surface. These fields trend parallel to, and are sourced by, deeply buried transpressive, northeast-to-southwest trending faults. In the more distal, deeper water regions, mobile shales are expressed in more plastic and fluidized eruption of mud volcano trains that parallel these same transpressive fault trends. Thick overburden deposited by the Orinoco Delta inhibits surface expression of mud mobilization in the proximal shelfal areas. In contrast, thinning overburden in distal regions allows faults to cut the seafloor and provide conduits for migration of deeper hydrocarbons to the seafloor surface.

Impact of Salt Movement on Fluvio-Lacustrine Stratigraphy and Facies Architecture: Late Triassic Chinle Formation, Northern Paradox Basin, Southeast Utah, USA

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Abstract

Continental depositional systems influenced by salt movement are characterized by rapid lateral and vertical facies changes that are difficult to predict at a reservoir scale. This study presents preliminary observations and interpretations of the Late Triassic Chinle Formation of the northern Paradox Basin, southeast Utah, USA, as a possible outcrop analog to subsurface reservoirs due to its extensive 3D exposure across a range of salt structures that were active during its deposition. Salt movement commenced prior to Chinle Formation deposition, when active structures included buried salt anticlines, salt walls exposed at surface, and salt withdrawal minibasins.

In the northern Paradox Basin, regional subsidence and climate controls are locally overprinted by the impact of halokinesis, which results in the break down of the regional Chinle Formation lithostratigraphy. Analysis of field exposures in this area allows the formation to be divided locally into five informal lithostratigraphic units bounded by mappable surfaces. Depositional environments include lacustrine, fluvial, and aeolian. The local stratigraphic framework allows salt-sediment interaction to be recognized by localized (km-scale) stratigraphic thickness variations, angular stratal relationships, and changes in facies architecture. Areas of active salt evacuation (*e.g.,* rim synclines and salt-withdrawal minibasins) are characterized by expanded stratigraphic thickness, preferential development and preservation of fine-grained floodplain and lacustrine deposits, and convergent or deflected paleocurrents. Salt walls that were exposed at the surface are characterized by the absence of strata, and the occurrence of rotational unconformities; they also have deflected paleocurrents and abundant reworked sediment into directly adjacent areas. Buried salt structures, active at depth, are also associated with subtle thickness variations and sediment slumping down their paleoslopes.

3D Structural Restoration of Ponded-Basin Turbidite Reservoirs in a Linked Extensional-Compressional Salt Basin, Holstein Field, Deep-Water Gulf of Mexico

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Abstract

The Holstein Field comprises multiple, ponded-basin turbidite reservoirs deposited in a mini-basin above allochthonous salt in southern Green Canyon, Gulf of Mexico. The mini-basin formed above a condensed shale section detached by gravity sliding from the underlying salt and bound by a linked extensional-compressional system of faults (updip to downdip) and has oblique- and strike-slip deformation on the margins. This deformation had direct control on the sediment entry and exit points. Associated synclinal and anticlinal structures influenced seafloor topography, depositional patterns and facies. The evolution of this structural system continued with punctuated episodes of fill-and-spill turbidite deposition. Although several successive reservoir intervals filled ponded relief and shared common characteristics, the gross basin system demonstrated an offset-stacking pattern onlapping updip, normal to sediment input direction.

High-resolution seismic and early well control resolve critical details of reservoir architecture for development planning, but steep structures and multiple episodes of faulting on the reservoir margins locally degrade seismic imaging and introduce geometric complications to isopach mapping. A 3D structural restoration was applied to remove post-depositional structural overprint and to restore sequentially reservoir stratal geometries for facies mapping. The restoration provides a three-dimensional template of accommodation space at reservoir scale. A simple down-dip migration algorithm was used to model sediment dispersal within this template enabling prediction of vertical and spatial facies distributions, improving on existing datasets. The restoration investigated evolving topographic controls on deposition illustrating a detailed 4D story and provided quantitative estimates of basin relief for more rigorous sediment modeling

Interpreted Shallow and Deep-Water Depositional Systems of the Beltana Mini-Basin in the Northern Flinders Ranges, South Australia

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Abstract

Salt-sediment interaction in the Adelaide 'Geosyncline' of South Australia has had a pronounced influence on deposition of the Late Precambrian to Early Cambrian succession that is well exposed in the northern Flinders Ranges. In this area, mini-basins are effectively windows into the salt withdrawal-related sedimentary section. Depositional systems of mini-basins and associated syn-depositional synclines are characterized by interpreted shallow and deep-water facies. In this paper, shallow-water facies/sediments are defined as those deposited above storm wave base, while deep-water facies/deposits are classified as those deposited below storm wave base.

The mini-basins are interpreted to have formed by either a combination of salt withdrawal and salt dissolution (Breaden Hill Mini-basin), or salt withdrawal (Beltana Mini-basin). Salt dissolution troughs are characterized by marine sediments interpreted to have been deposited in shallow water on the floor of the mini-basin. In contrast, interpreted lowstand, basin floor and slope fans occupy the basal fill of salt withdrawal troughs.

The Beltana mini-basin, the model discussed in this paper, is a classic example of an interpreted salt withdrawal mini-basin. An angular unconformity overlies slumped, lowstand facies of the mini-basin and marks the transition to regressive sedimentation. Regressive sedimentation of the highstand systems tract in this model is followed by pronounced subsidence and abundant sediment supply, resulting in a localized 2- to 5-fold increase in the depositional thickness of tidal marine facies. Stacking patterns suggest these facies can be assigned to the aggradational wedge systems tract that onlaps the rising flanks of the mini-basin. A major angular unconformity caps this sequence, marking incision of sea floor valleys that are subsequently infilled with shoreface facies. Continued subsidence results in the formation of a broader syn-depositional syncline above the mini-basin. A submarine canyon directly overlies the axis of the main mini-basin fill. It can be traced updip to a location where a deep-water dolostone overlies a surface of terrigenous sediment starvation.

Salt withdrawal and sediment loading combined to drop the floor of the mini-basin, and as sediments of the mini-basin flanks were uplifted and rotated, the relative fall in base level resulted in canyon incision. As subsidence continued, over-steepening of the basin margin resulted in slump and debris flow facies derived from the wall of the mini-basin or the submarine canyon. These deposits were contemporaneous with, or closely followed by, deposition of a channelized, clast-supported breccia. Submarine canyons in mini-basins and syn-depositional synclines had no shallow-water, updip equivalent. Instead, the deep marine sediments, subsequently deposited, were assigned to the forced transgressive systems tract. Sedimentation was generally transgressive, but was punctuated by unconformity-based debris flows and channel-fill breccias.

The Beltana mini-basin model predicts a number of stratigraphic, structural and combination hydrocarbon trap types that can be tied to the sequential formation of major unconformities within the mini-basin.

Bathymetric Control on Paleocene Gravity Flows Around Salt Domes in the Central Graben, North Sea

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Abstract

North Sea Central Graben salt diapirs grew by both passive downbuilding and active compressional reactivation during deposition of large Paleocene age turbidite fans derived from the uplifted Scottish platform. Once downbuilding diapirs were buried by more than approximately 200 m of overburden, including some Late Cretaceous chalk, very little bathymetric relief (<20 m) was present over the salt domes, and turbidites could flow across the crests of the salt diapirs. Diapirs having less, or no, overburden present during the Paleocene created more bathymetric relief (ranging between approximately 100 to 300 m), which diverted turbidite flows around the diapirs. Consequently, sandstones are absent on the crest of these salt domes, and high angle onlap reflectors are present on the diapir flanks.

The turbidite sandstones close to the diapirs show large amounts of slumping and soft sediment deformation where the paleo-topographic relief was high during deposition (*e.g.,* South Pierce, Merganser diapirs). This can have a slightly detrimental effect on oil recovery, but apparently not productivity, if the affected sequence contains shales.

Some diapirs (*e.g.* Jenny and Kyle, Fig. 1) are flanked by Paleocene debris flows containing lithified chalk fragments and occasionally reworked Zechstein evaporites indicating that the salt diapirs were emergent, or had high local sea bed relief. These flows can constitute high quality reservoirs due to the large amount of inter-clast porosity and later fracturing.

This study indicates the importance of analyzing the thickness and nature of the overburden present above salt crests, and the sediment onlap patterns, when turbidite deposition took place. These observations can be useful in predicting the presence, or absence, of turbidites over the crests of salt diapirs.

Summary of Halokinetic Sequence Characteristics from Outcrop Studies of La Popa Salt Basin, Northeastern Mexico

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Abstract

La Popa salt basin of northeastern Mexico contains exceptional exposures of salt stocks, salt withdrawal basins, and secondary salt welds, so that the scale and geometry of structural and stratigraphic features created by salt movement can be examined in both plan view and cross section. Cretaceous through Paleogene strata exposed adjacent to diapiric structures in La Popa Basin are arranged into halokinetic sequences, which display onlap and thinning toward the diapirs and stratal geometries indicative of syn-depositional diapiric growth. Within the shelf depositional environment in La Popa basin, halokinetic sequences can be split into two end-member types (Type **A** and Type **B**) that differ in depositional facies, maximum degree of internal folding, amount of fault reactivation on unconformities, overall sedimentation rate, and distance of halokinetic sequence termination from the salt/sediment interface. The differences in attributes of these two end-member types of halokinetic sequences have important implications for reservoir quality, geometry, and continuity.

Petroleum Systems Analysis and Comparison of Inversion Structures (Turtles and Half Turtles), Eastern Salt Canopy Trend: Deepwater Gulf of Mexico

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Abstract

Since the initial drilling at Metallica and subsequent discoveries at Thunder Horse and Thunder Horse North there has been a significant increase in wildcat drilling activity in the Eastern Salt Canopy Trend of the deep water Gulf of Mexico. An additional discovery at Blind Faith and a series of dry-holes/non-commercial discoveries in the trend has shown, however, that the petroleum system characterizing this play type is more complex then previously thought. To date, eleven prospects targeting deep Miocene reservoirs in inversion structures have been drilled in the Eastern Salt Canopy Trend resulting in a geological success rate of 0.55. Our understanding of these petroleum systems and our ability to accurately assess the geological risk of prospects of this play type has evolved rapidly over the past 5 years as a result of deeper exploratory drilling and public availability of data from these wells. Regional and prospect scale structural mapping of proprietary pre-stack depth migrated seismic data, analysis of well logs, and interpretation of the stratigraphic relationships between inverted mini-basins provide the framework for this comprehensive summary and comparison of the petroleum systems characterizing this play type.

Structural and stratigraphic analysis of the Miocene inverted mini-basins in the Eastern Salt Canopy Trend reveals significant patterns with respect to reservoir, hydrocarbon charge and focus, seal and structural geometry. Discoveries in the trend are found within aerially restricted 4-way closures produced by structural inversion of primary depocenters and within related 3-way closures along the margins of the mini-basins against the allochthonous salt canopy. Structural features beneath and along trend to the Miocene inversion structures provides necessary migration conduits and hydrocarbon focus for these structural highs. Variability in reservoir quality with depth is related to complex burial/diagenetic histories and the proximity to thick salt. Structural inversion in the middle Miocene subsequent to significant periods of lowstand creates the laterally extensive top seal for these hydrocarbon systems during ensuing transgressive periods. Although our understanding of these petroleum systems has come a long way since the first hydrocarbon discovery at Thunder Horse, a large degree of geological uncertainty still exists. The ability to adapt to these evolving challenges and integrate new data as it becomes available will ultimately determine the long-term exploration success within this trend.

Emplacement and Evolution of Salt in the Alaminos Canyon Protraction Area, Gulf of Mexico

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Abstract

The Gulf of Mexico is one of the most prolific and challenging basins in the world to explore in for hydrocarbons in deep-water. Success in deep-water exploration is contingent on knowledge of depositional systems, as well as salt tectonic geology. Over the study area, which is located in the Alaminos Canyon protraction area, 3D pre-stack depth imaging of seismic data provides definition of salt emplacement and evolutionary history. In this region, shallow allochthonous salt may be sourced directly from the Jurassic Louann layer. Emplacement of this salt occurred along a series of low-angle and high-angle surfaces toward the Sigsbee Escarpment. This basinward moving salt evolved as a salt nappe system. The salt nappe progressively advanced upsection and basinward over long distances from its feeders. The quality of the resulting depth migrated image allows description of prospect types in the subsalt section. It also allows for the definition of the northeast termination of the Perdido Fold Belt and Sigsbee Escarpment in the study area.

Seismic Imaging at Conger: Lessons Learned in Gulf of Mexico Subsalt Imaging

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Abstract

The Conger Field is a significant subsalt discovery located in the northeastern portion of Garden Banks. Production from four subsea wells has been steady and is very prolific since first production started in November 2000. (Conger was discovered in late 1997.) Conger is partially beneath salt. Reservoirs consist of multiple, geopressured, high-quality turbidite sandstones at depths ranging from 19,500 to 21,000 feet. These reservoir sandstones exhibit acoustic impedance contrasts that give rise to distinct seismic amplitude anomalies when hydrocarbon filled. However, despite the strong impedance contrasts, overlying salt distorts the seismic image significantly, and the subsurface evaluation heavily relies on the well data and geologic analogs. To-date, production at Conger has been excellent, confirming the geologic model for the field; i.e., laterally continuous sandstone reservoirs with minimal faulting.

Slumps and Salt Tectonics at the Mad Dog and Atlantis Fields

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Abstract

The interaction of salt and sediment at the Sigsbee Escarpment controls the geohazard environment at the Mad Dog and Atlantis fields development areas. Understanding the role of salt tectonics, and its control of the shallow geologic setting of the Sigsbee Escarpment, is critical to evaluating the shallow geohazards of these fields. Exploration 3D, high-resolution 2D and 3D seismic data, autonomous underwater vehicle data (bathymetry, side-scan, sub-bottom profiling), piston cores, boreholes, and remotely operated vehicle observations all provide information regarding the seafloor and subsurface geologic setting, and, in particular, the role that salt tectonics plays in creating, or modifying, the observed geologic features.

On the seafloor, bathymetric data show distinct domains characterized by contrasting seafloor textures including dramatic differences in the style of seafloor slumping. We show that these differences are due to a combination of salt morphology, supra-salt stratigraphy, and faulting.

There are two primary modes of slope failure on the escarpment face: shallow-seated, small-scale slumping, and deeper-seated, amphitheater-shaped failures. We differentiate among fault systems and slope failures of different origin and relate these differences to seafloor geomorphic provinces and variation in the geometry and movement history of salt.

Both normal faults in the supra-salt section, and seaward dipping beds above the frontal salt monocline, can provide pre-existing and preferential failure planes for slumping at the escarpment front. These dip slope conditions control the slumping in the shallow-seated slope failure portions of the escarpment at both the southwest Mad Dog and northeast Atlantis field areas. Deeper seated slumps may be related to retrogressive failure facilitated by internal overpressures.

The unprecedented detail of the data sets in the Mad Dog and Atlantis field areas allows a detailed kinematic model to be developed for the Sigsbee Escarpment, and an improved assessment of the geohazards.

Basement Controls on Salt Tectonics: Results from Analog Modeling

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Abstract

Physical models of salt tectonics related to thick-skinned extension have been largely confined to 2D studies. An experimental program, utilizing silicone polymer and silica sand/ceramic beads as ductile and brittle analogs respectively, was designed to investigate the 3D relationships between salt diapirs and a complex, bimodal, basement fault system during major extension and minor inversion events.

During extension, intersection points in the basement fault system generate complex, single, 2-way, or 3-way flap structures in the overburden localizing cover deformation and footwall diapiric activity on the rift margins. Flap structures and associated diapirs are located adjacent to, but diagonally inboard of, the basement intersection points and consist of convex-to-the-hanging wall fault segments that are gradually breached by rising polymer with increasing extension. Major diapirs that attain passive status accommodate much of the continued basement extension through downbuilding processes, resulting in heavily segmented basin margins. Intra-basin horst systems develop inward-dipping grabens cored by a major salt wall during initial extension. Axial flow along this structure feeds growing diapirs. Grounding of the brittle overburden results in source cut-off and deflation of the salt wall due to continued expansion of the cover graben by extensional processes.

During subsequent inversion major diapirs are reactivated, exhibiting rapid active rise through the overburden, suggesting that buoyancy forces associated with diapirs play a major role in their reaction to subsequent tectonic stresses. Diapir crests and entrained salt bodies are nucleation sites for the development of high-level, commonly rootless, brittle reverse faults.

Author Index

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