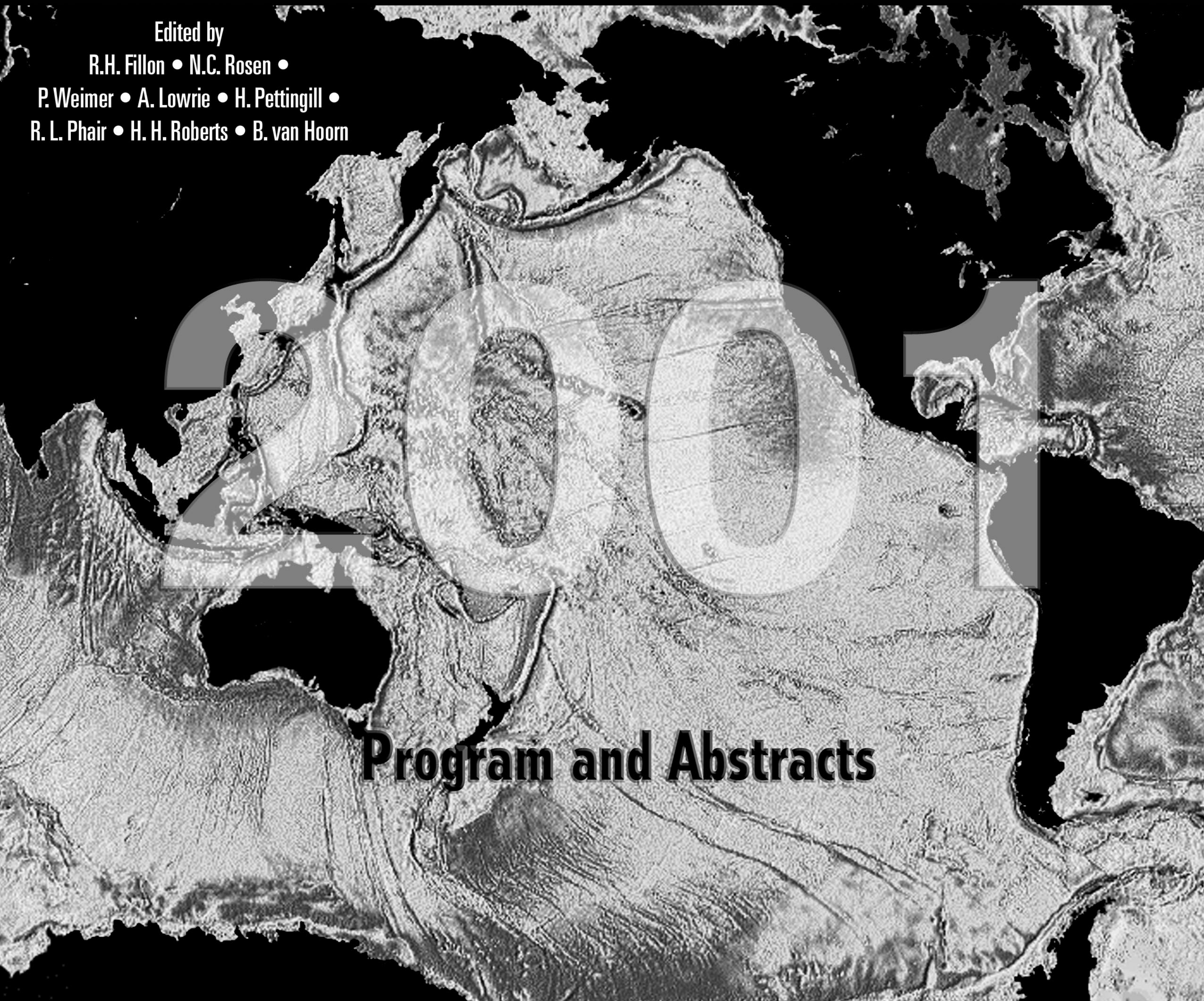
Petroleum Systems of Deep-Water Basins: Global and Gulf of Mexico Experience



Edited by
R.H. Fillon • N.C. Rosen •
P. Weimer • A. Lowrie • H. Pettingill •
R. L. Phair • H. H. Roberts • B. van Hoorn

2001

Program and Abstracts

Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation
21st Annual Bob F. Perkins Research Conference
December 2–5, 2001
Houston, Texas

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Foreword

The search for petroleum to meet society's demands for energy in the 20^{th} century has continually challenged those in our profession to better understand the earth and its systems. On the threshold of the 21^{st} century, with the significant advances in deep water seismic imaging, drilling, and production-technology that have been achieved in the last decade, the demand for more detailed understanding of deep water-deep-basin petroleum systems is intensely felt by all of us involved in the earth sciences.

One of the key elements of deep water-deep-basin petroleum systems, the *reservoir*, was the focus of last year's excellent GCSSEPM Research Conference "Deep Water Reservoirs of the World." That conference amassed, presented, and compiled in its CD-ROM proceedings volume a tremendous amount of reservoir information that is of great value to the petroleum industry as it steps forward to meet the demands of the new century.

The goal for this year's conference is to expand on last year's theme by including other key elements of the petroleum system. We are pleased that the international earth science and exploration community stepped forward enthusiastically to summarize the latest deep water exploration strategies in frontier areas around the world. Topics to be presented in the 2001 conference span the globe, from the ultra-deep Gulf of Mexico to the deep water basins of the Falklands, and offer new insights into the complex elements of deep water basin analysis including the tectonic framework of passive and active margin basins, deep-basin evolution, hydrocarbon maturation and migration, structuring, salt tectonics, and evolution of deep-basin siliciclastic and carbonate deposystems.

This year's conference is truly international with 134 authors and co-authors from 10 countries presenting 49 papers, which examine basinal and deep water portions of Nova Scotia, the U. S. Gulf of Mexico, Mexico, Guatemala, Belize, the Caribbean, Trinidad, Colombia, Peru, the Falklands, Spain, Morocco, Equatorial Guinea, Cote d'Ivoire, Angola, Tanzania, New Zealand, Southeast Asia, and Azerbaijan. The authors represent industry, government and academic institutions in the United States, Angola, Azerbaijan, Canada, Colombia, England, Italy, Mexico, Peru, Trinidad, New Zealand, Scotland, and Spain.

All of the authors deserve a great deal of praise for the huge amount of effort they put into preparing their manuscripts, and for constructing wonderful illustrations that will make the CD-ROM a valuable reference work in support of hydrocarbon exploration for the next decade. The organizations they represent also deserve our heartfelt gratitude for their foresight in supporting and encouraging their professional staff in sharing a great deal of valuable information. With the mobility of the modern workforce it is more than ever in their best interest to encourage such cost effective transfer and exchange of earth science knowledge.

With the large and diverse array of papers submitted to the conference this year, the program advisory committee could not have pulled everything together in less than a year without the vigorous support of reviewers, several of whom also had their own papers to get out and all of whom were busy with their regular work. Without their help, publication of the high-quality, refereed CD-ROM proceedings volume in such a short time would not have been possible. We thank the following individuals for providing excellent reviews under very tight time constraints:

Rob Alexander, Dick Buffler, Rion Camerlo, Ed Colling, Ed Denman, Gren Draper, Paul Lawless, Allen Lowrie, Ernie Mancini, Liz McDade, Henry Pettingill, Ron Phair, David Pyles, Harry Roberts, Paul Thacker, Berend van Hoorn, Paul Weig, and Paul Weimer.

As chief organizer and link between authors, reviewers and the Foundation, I also thank program advisory committee co-chairs and members, who represent a true cross section of earth science disciplines, for serving in as many capacities to bring this conference together as possible. They worked diligently to plan, to entice contributors from around the world, to review manuscripts and, in several cases, to prepare their own contributions. The committee members: Allen Lowrie, Henry Pettingill, Paul Weimer, Dick Buffler, Liz McDade, Ernie Mancini, Ron Phair, Harry Roberts, Ed Denman, Berend van Hoorn, Nancy Engelhardt-Moore, John Armentrout all deserve our gratitude. Each helped in various capacities, and each in different stages of planning and execution.

We thank Gail Bergan for her patience with the continuing tension of papers arriving always at the last possible moment and for turning out a professional CD-ROM volume in spite of everything. To Jerri Fillon, scheduler, organizer and mailroom administrator in this endeavor we offer our sincerest thanks. And last, but absolutely not least, to Norm Rosen, the Executive Director of the GCSSEPM Foundation, we offer our deep gratitude and admiration for continuing on in the spirit of our old friend Bob Perkins, making this entire conference series possible.

All connected with this conference and proceedings volume realize that this has been a difficult time for the United States, its citizens and residents. To all those attending who may have experienced personal losses we express our sincere sympathy.

The 2001 conference is certainly one of the strongest and most significant conferences in a series that over the years has provided our profession and industry with an invaluable and timely source of knowledge. You will, I think, over the next few days find much to excite you in the oral and poster presentations, and when you open the CD-ROM you will find a reference work that will occupy an important niche in your offices for years to come.

Dick Fillon
December 2001
Houston, Texas

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Petroleum Systems of Deep-Water Basins: Global and Gulf of Mexico Experience

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Program and Abstracts

Sunday, December 2, 2001

4:00–6:00 p.m. Registration—Grand Foyer

6:00–8:00 p.m. Welcoming Reception and Poster Preview—Grand Pavilion

Monday, December 3, 2001

7:00 a.m. Continuous Registration—Grand Foyer

7:45 a.m. Welcome: Nancy Engelhardt-Moore, Chairman of the Board of Trustees, GCSSEPM Foundation—Grand Pavilion

7:50 a.m. Introduction and Welcome: Dick Fillon, Program Chairman

Session I—Global and Gulf of Mexico Deep-Water Exploration

Presiding: **Paul Post, Paul Weimer**

9:30 a.m. **Refreshment Break and Poster Viewing**

Tuesday, December 4, 2001

Session III—Global and Gulf of Mexico Deep-Water Exploration

Presiding: **Dick Fillon, Dan Worrell**

Session IV—Global and Gulf of Mexico Deep-Water Basin Evaluation

Presiding: **Ernie Mancini, Harry Roberts**

Wednesday, December 5, 2001

Session V—Global and Gulf of Mexico Deep-Water Basin Evaluation

Presiding: Roger Sassen, Berend van Hoorn

Posters Only: Exploration and Deep-Water Basin Evaluation

World-Wide Deep Water Exploration and Production: Past, Present and Future

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Abstract

Exploration and production in deep water (>500m) has expanded greatly during the past decade, and approximately 57 BBOE has beeen discovered, more than half since 1995. Despite this rapid emergence, deep water remains an immature frontier, accounting for less than 5% of the current world-wide total oil-equivalent resources. Only about 20% of the discovered deep water resources are developed and less than 5% have been produced.

The global deep water exploration success rate was about 10% until 1985, but has since averaged approximately 30%, driven by remarkable success in the Gulf of Mexico and West Africa. Whereas the world-wide discovery of giants has fallen off in recent decades, the discovery rate of deep water giants is rapidly increasing.

Most of the exploration activity has been concentrated within only three areas of the globe, as a majority of the discovered resources in the Gulf of Mexico, Brazil, and West Africa. Consequently, large portions of the world's deep water margins remain lightly explored. Deep water gas exploration is extremely immature, reflecting current infrastructure and economic limitations but destined to become a major future focus.

Most of the currently most active deep water exploration frontiers and associated resources are located along passive margins, downdip from productive Tertiary delta systems, in depocenters confined by mobile substrate. In simplest terms, petroleum systems responsible for the majority of the discovered resources can be classified as either early rift (lacustrine) or later passive margin (marine). Ninety percent of the resources are reservoired in turbidites, primarily of Cenozoic age. A key success factor is targeting "high kH" reservoirs, which have high flow rates and well ultimates. These commonly occur within ponded minibasins associated with mobile substrate, where stacked turbidites result in high net pay per area. Other key exploration success factors have been seismic DHI's, identification of stratigraphic traps, and improved reservoir architecture prediction. Leading companies are moving into non-DHI plays and other geologic settings, including pre-Tertiary objectives and areas lacking major updip reserves.

Recent trends suggest several themes for future deep water exploration: (1) a continuation of established plays, which are still at an immature stage of drilling, (2) going beyond the established formula to basins lacking updip production, unconfined basins, compressive margins, and targeting pre-Cenozoic, non-turbidite, and non-DHI objectives, (3) increased gas exploration, as pipeline networks and liquefaction technology advance in conjunction with increased consumption, (4) going deeper, both ultra-deep water and deeper drilling depth, including subsalt, sub-detachment, and sub-volcanic targets, and (5) new business opportunities which may arise in areas currently not open due to government monopolies, moratoriums, and international boundary disputes. New frontiers having these characteristics are being actively leased, but many have yet to experience significant drilling, so it remains to be seen whether the deep water play will continue to add reserves at the rate of recent years.

Petroleum Systems of the Deep Water Scotian Salt Province, Offshore Nova Scotia, Canada

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Abstract

The Scotian Basin, under Atlantic Canada's continental shelf and slope, encompasses a corridor 100 to 150 km wide by 900 km long on the southeastern continental slope of the province of Nova Scotia, Canada. Since 1967, a total of 103 exploration wells have been drilled in the shelf portion of the basin within the setting of the Sable subbasin.

The Scotian Basin is divided into a series of geologically distinct subbasins. Opening occurred during the Middle to Late Triassic, in response to separation of North America from Africa. During this time, synrift red beds, restricted marine dolomites and halites of the Eurydice, Iroquois and Argo formations, respectively, have been deposited. From the Early Jurassic to the end of the Cretaceous, the basin continues to subside, infilling with significant quantities of fluvio-deltaic and shelf sandstones. During lowstands, incision of the shelf carries sands down the paleoslope into deep marine environments, where they are deposited within a variety of subaqueous facies. The Tertiary-aged Banquereau Formation consists of fluvial, deltaic, and deep water sandstone environments.

Although tectonically passive, deep water portions of the Scotian Basin contain the Scotian salt province. This subbasin is extensively deformed by halokinetic movement of Late Triassic Argo Formation halite, which mobilized to form swells, walls, ridges, and domes. Sedimentation and play-types vary considerably along the 900 km of the salt province within water depths of 1,000 to 3,000 metres with the potential for a number of distinct petroleum systems throughout the subbasins and include potential subsalt exploration targets.

Mesozoic Ultra-Deep Water Potential of the U.S. Gulf of Mexico—Conceptual Play Development and Analysis

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Abstract

A series of conceptual Mesozoic plays was defined in the ultra-deep water U.S. Gulf of Mexico by interpreting a 2x2 mile grid of 2-D seismic data covering an area of approximately 39,000 square miles basinward of the Sigsbee salt canopy. Time maps on the seafloor, approximate Cretaceous/Tertiary boundary, Mid-Cretaceous Sequence Boundary, approximate Jurassic/Cretaceous boundary, top autochthonous salt, and “basement” seismic events were constructed and converted to depth using regional interval velocities.

Conceptual plays in the western and central planning areas of the Gulf of Mexico include fold belts and buried hills; the latter have been subdivided into structural, stratigraphic-detrital, and drape plays.

In the eastern planning area, a structural play that is characterized by salt rollers, autochthonous salt swells, pinnacle salt structures/vertical salt welds, and salt growth and/or salt withdrawal (turtle) features was delineated in the West Florida Salt Basin.

Reservoir analogs for each play were identified by searching worldwide for fields having similar trap type and reservoirs of comparable depositional environment. Monte Carlo simulations were run to analyze and develop distributions of the analog data. Petroleum system analysis was performed to incorporate, describe, and display the elements (source, reservoir, and seal) and the processes (trap formation, generation–migration–accumulation, and critical moment) associated with each play. Play risks were evaluated, described, and presented using a “traffic light” ranking system. The results of this study suggest that in the ultra-deep water Gulf of Mexico, these and other conceptual Mesozoic plays may offer a variety of future high-potential exploration opportunities. This paper is a synopsis of over 2 years of work, and not all of the details can be presented in a paper of this length.

Intimate Relations: Interaction of Tectonics and Sedimentation in the Formation of Roller-Style Fault Families and Traps in the Eastern East Venezuela Basin, Trinidad and Venezuela

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Abstract

The hydrocarbon-prolific eastern East Maturin Basin of Trinidad and Venezuela is filled with more than 40,000 ft of deltaic, fluvial/estuarine and deep marine sands and shales deposited in a rapidly subsiding basin along the triple junction of the westward-subducting Atlantic plate and the obliquely colliding Caribbean and South American plates. The basin is characterized by several northwest-southeast-striking roller faults across which the Plio-Pleistocene expands to the northeast. Several thrust-cored anticlinal ridges trend northeast to southwest, and major hydrocarbon fields are aligned along them.

The last Cretaceous shelf-break trends east to west and has an important influence on the underlying Miocene interval, which appears to thicken to the north across this paleogeomorphic feature. Increased thickness of Miocene shales along the northern margin of the basin results in increased shale diapirism in this same region. Bidirectionally thickened bow-tie anticlines form, whose crests migrate to the east as they become younger, and associated secondary roll-over faults emerge. These roll-over faults partition hydrocarbon accumulation within the bow-tie structures. Thinning of Miocene shales along the southern margin of the eastern East Maturin Basin decreases the influence of diapirism, resulting in formation of monodirectional thickening of section to the west and thinning to the east. Thus monoclinal structures contain the majority of structural traps in the footwall of younger roller faults. Shale rollers or secondary roll-over faults are rare.

Understanding the nature and influence that previous paleogeography can exert on a basin's structure, migration pathways, and accommodation distribution can lead to improved predrill and postdrill assessment of hydrocarbon systems risk.

Regional Mapping and Maturity Modeling for the Northern Deep Water Gulf of Mexico

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Abstract

Regional mapping and maturity modeling show distinct patterns that are characteristic of the complex petroleum system in the deep water portion of the northern Gulf of Mexico (GOM). Maturity for source rocks within the Cretaceous and Jurassic sections tends to increase from the abyssal plain to the salt canopy province as the overlying section thickens. One striking exception to this trend is the Cuba fracture zone, which extends southeast from South Pass to the southern GOM. Observed as a strong magnetic anomaly in basement maps, the Cuba fracture zone shows other impressive anomalies. Heat flows tend to increase approximately 25% along the zone relative to calibration points on either side, which suggests that it is an important crustal feature. Empirically, the Cuba fracture zone appears to be a major dividing point in the north central GOM, where on its northeast side gas appears to be much more prominent than on the southwest side.

Mapping the GOM on a regional scale required the integration of 2D and 3D seismic data, gravity and magnetic data, and large-scale velocity models that include salt for proper depth conversion. Basement maps were generated from the integration of gravity and magnetic data with acoustic basement mapping from seismic in the abyssal plain. A variety of key chronostratigraphic horizon depth maps were generated from a regional velocity model that included salt and was applied to multiple time horizons. Probably the most difficult mapping task was to make accurate correlations between areas with enormous amounts of data (*e.g.*, 3D seismic) and those with a paucity of data (*e.g.*, 2D seismic in subsalt sections). Developing maturity models required an accurate set of stratigraphic depth maps, calibration and mapping of heat flow on a large scale, and the appropriate choice of source rock horizons and associated properties to evaluate.

Results from this regional evaluation indicate that there is a definite relationship between source rock maturity and major oil and gas discoveries. The timing of hydrocarbon generation and migration relative to the timing of structuring is critical to each successful discovery. This can be evaluated on a regional scale when maturity results are placed in context with general structural trends.

Falkland Islands: Past Exploration Strategies and Remaining Potential in Under-Explored Deepwater Basins

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Abstract

The Falkland Islands are surrounded by four major sedimentary basins (the Falkland Plateau basin to the east, the South Falkland basin to the south, the Malvinas basin to the west, and the North Falkland basin to the north). The basins underwent complex rifting from the ?Triassic through Valanginian, during fragmentation of Gondwanaland, before being subjected to Cretaceous thermal sag and Cenozoic uplift coincident with Andean compression and the development of overthrusting along the plate boundary to the south.

Only the North Falkland basin was drilled; six wells were spudded back to back by four operators who formed a unique alliance in 1998 to undertake all of the logistics and support work to facilitate a multi-well drilling campaign. Drilling took place in water depths between 250 and 460 metres. Five of the six wells had oil shows, mostly in post-rift sandstones located immediately above the main source rock interval. Live oil was recovered at the surface from one of the Shell wells; significant levels of gas were also recorded in some wells. Although none of the wells encountered commercially viable accumulations, it is possible that up to 60 billion barrels of hydrocarbons could have been expelled in the basin. Post-mortem analyses of the petroleum system revealed why the wells were non-commercial and pointed the way to future commercial success.

As well as the remaining potential of the North Falkland basin, the other large, deep water to ultra-deep water basins around the Islands are under explored and are covered only by reconnaissance seismic data. Oxfordian to Aptian claystones present in DSDP boreholes indicate a potentially prolific hydrocarbon yield from Type II kerogens. Modelling suggests that the source rocks are possibly mature for oil generation at about 3,000 metres below seabed, and numerous play types can be predicted on the basis of the existing seismic data and by correlation with analogous basins.

The paper will highlight the entire basin potential of the offshore Falklands region (petroleum systems, sequence stratigraphy, tectonic evolution, etc.), evaluate the pros and cons of the unique exploration sharing strategies adopted so far, and outline the exploration and production challenges posed by the particularly sensitive environmental concerns in the region.

Basement Controls on Hydrocarbon Systems, Depositional Pathways, and Exploration Plays Beyond the Sigsbee Escarpment in the Central Gulf of Mexico

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Abstract

Improved understanding of the interaction between basement structure, salt tectonics, and depositional systems can be of great value in tract evaluation and resource assessment, particularly in subsalt areas or under-explored, emerging plays. One such area is the Abyssal Fan Play of the ultra-deep water Gulf of Mexico. Here, an ordered basement fabric appears to have influenced the vertical juxtaposition of potential Mesozoic source rocks, Tertiary reservoirs, and vertical migration pathways.

Examination of central Gulf of Mexico tectonic elements, structural features, salt systems, and field distributions reveals patterns of systematic right-lateral offsets along trends that approximate North Atlantic fracture zones. Regional maps of Mesozoic and Tertiary horizons generated from a modern 2x2-mile 2-D seismic grid were used to interpret transfer fault trends and delineate Mesozoic rift basins beneath the abyssal plain. These basins are seen to be right-stepping across a series of northwest-southeast trending transfer faults in southern Atwater Valley, Walker Ridge, and Lund. These basins may contain source rocks of Jurassic or Cretaceous age. Dramatically high-standing basement blocks beneath the abyssal plain may be Cretaceous volcanic edifices that exploited the transfer fault zones during a period of post-rift tectonism.

Transfer fault zones may have served as sediment fairways through the salt canopy and fold belt throughout the Tertiary. Point sources for Miocene deep water fans emanate from the Mississippi Fan Fold Belt where fold axes are offset along transfer fault zones. The middle Miocene section contains an apron of fans just outboard of the Sigsbee Escarpment, but is condensed over most of southern Walker Ridge, Atwater Valley, and Lund. However, seismic facies suggest that some sand-prone middle Miocene fans were directed by basement-controlled fairways beyond the southern margin of Lund and Lund South. Across the northeastern half of the abyssal plain, within the corridor between the Cuban and Campeche fracture zones, regional dip is to the southwest. Across southwestern Lund and western Walker Ridge, to the west of the Campeche fracture zone, regional dip is to the northwest, as the section climbs toward the Yucatan block. This basin configuration has focused deposition toward southeastern Lund, where middle Miocene fans onlap the outer reaches of the Campeche rise.

Combination structural-stratigraphic traps in middle Miocene fans overlying uplifted basement or Cretaceous volcanic edifices can be sourced from adjacent rift basins by a series of regional joints and fractures. These elements comprise a new play that extends the Miocene frontier 150 miles south, to the limits of U.S. waters.

Processes and Events in the Terrane Assembly of Trinidad and Eastern Venezuela

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Abstract

Neogene-Recent arrival of the Caribbean plate and subsequent development of the southern Caribbean plate boundary zone as well as coeval deposition of Orinoco deltaic sediments in Eastern Venezuela-Trinidad have profoundly changed the region's earlier basin setting, including some very large vertical and horizontal displacements of original tectonic elements and depositional systems. Plate kinematic analysis provides the geometric and temporal framework in which to see past these late developments and to deduce the region's earlier paleogeographic evolution and constrains the primary setting, style, and timing of basement structure in the region's shallow-water, and deep-water continental margins through time. Palinspastic restoration of deformations, terrane accretions, and sedimentary additions to the region's continental areas back through time to the breakup of Pangea allows fine-tuning of the kinematics and prediction of parameters such as paleo-heatflow, paleo-sedimentary provenance, and aspects of source and reservoir potential.

In Eastern Venezuela-Trinidad, Jurassic rifting has produced a serrated crustal margin, along which rift segments are oriented ~070° and separated by sinistral transfer zones at ~140°. A Late Jurassic-Cretaceous "passive" margin along the proto-Caribbean seaway developed above this basement, but sinistral shear between South American and Bahamian crusts along the Guyana Escarpment may have caused continued tectonism into Early Cretaceous, prior to truly passive margin Late Cretaceous source rock deposition. Paleogene convergence between North and South America caused uplift and erosion in Venezuela's northern Serranía del Interior, the flyschoid depositional results of which are found in northern Trinidad. This is because the northern Trinidad depocenter, here called the Northern superterrane, was situated much closer to the Serranía at that time, as opposed to southern Trinidad. During Oligocene-middle Miocene arrival from the west and dextral-oblique arc-continent collision of Caribbean plate with the margin, the Northern superterrane strata have been translated east-southeast and imbricated with strata of the Southern superterrane, producing strong foredeep subsidence in the Maturín-early Southern basin.

Coeval strike slip faults such as Coche-North Coast may have taken up some of the strike-slip component of the oblique relative motion. Since the end of middle Miocene, the southeast Caribbean plate boundary zone has been dominated by east-west simple shear and relatively minor north-south shortening and extension adjacent to faults. A 3-stage model involving variable strain partitioning describes the tectonic and basin history of Eastern Venezuela and Trinidad for the last 12Ma. The various stages of development have produced exploration settings of different aspect across the greater Trinidad region.

Kinematic Evolution of the Gulf of Mexico and Caribbean

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Abstract

We present a series of 14 updated tectonic reconstructions for the Gulf of Mexico and Caribbean region since the Jurassic, giving due attention to plate kinematic and palinspastic accuracy. Primary elements of the model are

1. A re-evaluation of the Mesozoic break-up of Pangea, to better define the Proto-Caribbean passive margin elements, the geology and kinematics of the Mexican and Colombian intra-arc basins, and the nature of the early Great Caribbean Arc;
2. Pre-Albian circum-Caribbean rock assemblages are reconstructed into a primitive, west-facing, Mexico-Antilles-Ecuador arc (initial roots of Great Caribbean arc) during the early separation of North and South America;
3. The subduction zone responsible for Caribbean Cretaceous HP/LT metamorphic assemblages was initiated during an Aptian subduction polarity reversal of the early Great arc; the reversal was triggered by a strong westward acceleration of the Americas relative to the mantle which threw the original arc into compression (Pindell *et al.*, in press);
4. The same acceleration led to the Aptian-Albian onset of back-arc closure and "Sevier" orogenesis in Mexico, the western USA, and the northern Andes, making this a nearly hemispheric event which must have had an equally regional driver;
5. Once the Great Caribbean arc became east-facing after the polarity reversal, continued westward drift of the Americas, relative to the mantle, caused subduction of proto-Caribbean lithosphere (which belonged to the American plates) beneath the Pacific-derived Caribbean lithosphere, and further developed the Great arc;
6. Jurassic-Lower Cretaceous, "Pacific-derived," Caribbean ophiolite bodies were probably dragged and stretched (arc-parallel) southeastward during the Late Jurassic to Early Cretaceous along an (Aleutian-type) arc spanning the widening gap between Mexico and Ecuador, having originated from subduction accretion complexes in western Mexico;
7. A Kula-Farallon ridge segment is proposed to have generated at least part of the western Caribbean Plate in Aptian-Albian time, as part of the plate reorganisation associated with the polarity reversal;
8. B" plateau basalts may relate to excessive Kula-Farallon ridge eruptions or to now unknown hotspots east of that ridge, but not to the Galapagos hotspot;
9. A two-stage model for Maastrichtian-early Eocene intra-arc spreading is developed for Yucatán Basin;
10. The opening mechanism of the Grenada intra-arc basin remains elusive, but a north-south component of extension is required to understand arc accretion history in western Venezuela;
11. Paleocene and younger underthrusting of Proto-Caribbean crust beneath the northern South American margin predates the arrival from the west of the Caribbean Plate along the margin; and
12. Recognition of a late middle Miocene change in the Caribbean-North American azimuth from east to east-northeast, and the Caribbean-South American azimuth from east-southeast to east, resulted in wholesale changes in tectonic development in both the northeastern and southeastern Caribbean Plate boundary zones.

The Role of Salt in Gravitational Failure of Passive Margins

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Abstract

Salt along a passive margin facilitates and accommodates gravitational failure of the margin in several key ways. First, it serves as the basal detachment for a linked system of updip extension and downdip contraction that develops due to a combination of gravity gliding and gravity spreading of the sediment carapace. Second, proximal subsidence into salt and distal inflation of salt reduces the bathymetric slope and the associated gravity potential. Third, preexisting salt diapirs and massifs accommodate basinward translation of the overburden by lateral squeezing and the consequent extrusion of allochthonous salt. Fourth, allochthonous canopies can serve as additional detachment levels for gravitational failure. Deep water environments are where most of the shortening occurs, which is manifested as salt-cored folds, reverse faults, squeezed diapirs, inflated massifs, and extrusion of allochthonous salt. Extensional and strike-slip faults and associated salt deformation are also present, as are loading-induced features such as turtle structures and passive diapirs.

New Oceanographic Observations of the Gulf of Mexico Deep Waters

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Abstract

Recent deepwater current observations in the Gulf of Mexico suggest this environment is more energetic than previously observed. Data and modeling results suggest that the Gulf of Mexico behaves as a two-layer system. Coupling of waters above 1,000 m to waters below is still unresolved and remains a topic of further research. The upper layer circulation is dominated by the Loop Current (LC), Loop Current rings (LCR), and smaller scale eddies. Recent data reveal a rich field of eddies of 30–150 km diameters that influence the LCR and shelf-edge currents. The lower layer circulation is less understood. Currents of ~30 cm/s vertically unchanged below 1,000 m, but showing near-bottom intensification interpreted as topographic Rossby waves (TRW) are reported. These waves have 20–30 day periods, wavelengths of 150–250 km, and propagate westward at about 9 km/day. Recent current measurements at 2,000 m reveal even stronger speeds (~90 cm/s) 11 m above the bottom and a small vertical shear below 1,000 m typical of TRW with periods of ~10 days and wavelengths of 70 km. In this lower layer, models show the presence of deep cyclone-anticyclone pairs that move westward and interact with the bottom topography, creating intense bottom currents. Direct observations of large furrows, active at present, suggest strong (~100 cm/s) near-bottom currents. The role of steep slopes in the generation of large amplitude TRW's is at present unknown. It is also unknown if the observed strong ocean currents are responsible for the large furrows at the sea floor.

The Rio Muni Basin of Equatorial Guinea: A New Hydrocarbon Province

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Abstract

The Rio Muni basin underlies the continental shelf of the west African republic of Equatorial Guinea, located between Gabon and Cameroon. The basin is situated above a section dominated by a northeast-southwest trending oceanic fracture zone and its continental extension. This fracture zone constitutes the boundary between the Equatorial Atlantic margin and the West African salt basin.

Despite its location between the prolific hydrocarbon provinces of the Niger delta to the north and the Gabon coastal basin to the south, the Rio Muni basin has been overlooked by the industry for much of the last decade. Previous wells have proved a viable source rock, but no accumulations. Triton Energy licensed Blocks F & G in 1997 and drilled the Ceiba 1 discovery well in 1999, proving a new hydrocarbon system in the deep water, Late Cretaceous post rift sequence. Deformation by Santonian-Coniacian transpression caused uplift of the shelfal area and deposition of a thick, slope fan sequence. Contemporaneous salt deformation of rafted deposits and the development of a base of slope compressional belt are also evident. The resultant turbidite sequences form the reservoirs in the Ceiba discovery, which has been tested at 12,400 BOPD. Both Late Cretaceous and Tertiary turbidite reservoirs form exploration targets in the basin; these may be charged by a deep water source kitchen from which earlier, shelfal wells were shadowed.

Examples of Deep-Water Salt Tectonics from West Africa: Are They Analogs to the Deep-Water Salt-Cored Fold Belts of the Gulf of Mexico?

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Abstract

Deep water structures at the basinward edge of African salt basins display very different geometries, some of which are directly comparable to the deep water Mississippi Fan and Perdido fold belts of the northern Gulf of Mexico. To conduct a comparative structural analysis, regional reflection seismic transects were constructed across the continental margins of Morocco, Equatorial Guinea, Gabon and Angola.

All the salt-cored deep-water fold belts are driven by gravity, where updip extension is accommodated by downdip compression along a basin-wide salt detachment. Differences in the end result are attributed to several factors: (1) basins containing syn-rift salt compared to post-rift age salt basin settings generally provide a less efficient basin-wide detachment; (2) narrow and steep continental margins tend to enhance the compressional structures at the toe of the slope; (3) sharp, fault-bounded termination of the original basinward depositional limit of the salt may result in the lack of a foldbelt, regardless of the tectonic position of the salt.

Whereas the Mississippi Fan fold belt is a fairly close structural analog to the Tafelney foldbelt offshore Morocco, the Perdido fold belt appears to be fairly unique and is not analogous to any fold belts in African salt basins. Conversely, from a northern Gulf of Mexico perspective, some deep water toe-thrust zones in West African salt basins may be regarded as quite unusual. Therefore salt-related exploration experience gained in the Gulf of Mexico region should be applied to West African salt basins with some caution.

The Hydrocarbon Habitat of the Agadir Basin Offshore Morocco

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Abstract

The Agadir basin is situated off the Moroccan Atlantic coast and the Canary Islands. It comprises some 80,000 sq km of shelf and deep water acreage, and has been explored by 16 wells, all drilled on the shelf margin. The deep water basin remains undrilled at present.

In 1998, Shell acquired 2,000 km of 2D seismic in the Agadir deep water basin, where previous exploration had revealed the presence of a mobile salt substratum in an area characterised by the presence of a world-class source rock (the Albian -Turonian Tarfaya Shale). On the Jurassic carbonate and Cretaceous clastic shelf, significant oil shows had been discovered during the seventies.

Key results of the 1998 to 2000 Agadir Basin exploration are:

1. The basin is highly structured, due to interaction of the Atlas compression with passive margin extension and halokinesis. This structuring creates a large number of potential traps.
2. An Atlas-sourced fluvial system delivers Tertiary turbidites to the basin. Late Cretaceous and Palaeocene sandstones appear to be derived from the Moroccan Meseta. A Jurassic to Cretaceous delivery system from a more southerly source is expected to shed older turbidites into the Agadir basin. Erosional scours originating on the platform confirm that the Cretaceous shelf sands have been transported into the basin.
3. Reservoir quality is a possible concern in an area where carbonate rocks abound in the source area. The main objective in the northern part of the Agadir basin is a Late Cretaceous to Paleogene reservoir play, which ties back to shelf and fluvial sandstones outcropping onshore in the Souss valley and predates the formation of the High Atlas range. Secondary objectives occur in the Neogene and in the Lower Cretaceous to Jurassic intervals.
4. Geochemical modelling supported by the shows in platform wells and the abundance of oil slicks suggests that an active oil charge system is working in the basin. The world-class Tarfaya Shale is likely to be mature over large areas. Older source rocks are likely to further contribute to oil (and gas) charge. They comprise Oxfordian and Liassic shales, but also more speculative Westphalian coals and Silurian shales.
5. Halokinesis is active over the entire area, but increasing in intensity and becoming progressively younger towards the northern part of the Agadir permit, where compressional activity has focused. Locally therefore trap integrity and/or charge timing may form an issue for truncation plays against piercing salt domes. Other play types in the Agadir basin consist of anticlinal closures over deep-seated salt swells, fault-related structures and stratigraphic traps.

Exploration in Deep Water Basins…Where Next?

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Abstract

Exploration success in the first two decades of deep water exploration has been highly focused on a particular basin type: Atlantic rift margin basins draped by thick deep water clastic strata, deposited downdip of large Tertiary drainage systems and above a mobile substrate of shale or salt. Most are downdip extensions of working petroleum systems on the adjacent shelf and onshore. Reasons for the preponderance of discovery volume to date in this basin type include: 1) a very high density of structural and stratigraphic/structural leads and prospects; 2) the ready availability of high quality reservoir in deep water channels and fans; and, 3) focused maturation of oil-prone source rocks caused by the Tertiary depocenters. The source rocks are varied and have been found in synrift, post-rift and deltaic settings. Trap types have included channels over deep-seated salt-or-shale structural highs, flanks and faulted flanks of salt or shale minibasins, and submarine fans draped over underlying structural highs. Exploration in plays in the upper slope portions of some of these basins is beginning to show signs of maturing, as new play development continues to move outboard and deeper. In the latter part of the last decade exploration plays have been made in the distal-most structured portions of some of these basins.

Where then might the next prolific frontier basins and/or plays in the deep water theatre be found? Many ideas that are being pursued in our industry, or are still on the drawing boards, include:

1. Moving still farther downdip of these focus basins into the largely unstructured basin floor fans that lie on the toe of slope and abyssal plain. Although analogs exist for successful traps in this setting given at least low angle structural inclination, clear difficulties include the occurrence of thermal maturity and the inferred low density of traps.
2. Moving deeper within these focus basins, especially to non-amplitude supported and/or subsalt objectives.
3. Moving laterally from the mobile substrate basins into less structured provinces nearby, that still have sufficient sedimentary section to provide reservoir and mature source rocks.
4. Exploring other, similar mobile substrate basins.
5. Exploring basins with other structural origins, for example transform margins, or fold and thrust belts in active margin settings.
6. Exploring non-turbidite (*e.g.*, carbonate) reservoirs in deep water settings.

These and other more novel play concepts will be required to continue the rapid growth seen in the past two decades of the deep water play.

Petroleum Potential of the Deepwater Taranaki Basin, New Zealand

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Abstract

The New Zealand Exclusive Economic Zone (EEZ) contains at least six large deep water basins: the deep water Taranaki basin, the Raukumara basin, the Pegasus basin, the Head of the Bounty trough, the Great South basin and the Solander trough. Structural styles vary from rift basins through strike-slip dominated basins to major accretionary prisms. Source rocks encountered include coal measures, black marine shales, and lacustrine facies. Sedimentary thicknesses, heat flow studies, and basin modeling supported by production and numerous seeps in the shelf and onshore, suggest that these basins may be prolific hydrocarbon producers in the future. Recent developments suggest that the most promising of these basins is the deep water Taranaki basin, outboard of New Zealand's only producing basin to date.

The petroleum histories of most of these basins began with the Late Cretaceous break-up of Gondwana and the formation of rift basins. In onshore New Zealand and on the continental shelf, many of the source rocks for the productive Taranaki basin were deposited at this time. The earliest sediments to be deposited were commonly fluvial, lacustrine, deltaic and nearshore facies followed by an increasing marine influence as the region foundered through the Paleogene.

The Neogene saw the formation of the present plate boundary and the emergence of New Zealand in response to plate collision. Many of the more spectacular structures in the New Zealand sedimentary basins were formed during the Neogene. Meanwhile, the deep water basins away from the plate margin continued a quieter development. Some inversion occurred, but not to the extent of the nearshore and onshore regions. This relatively gentle structural evolution increased the likelihood of discovering large hydrocarbon fields in unbreached structural traps.

Stratigraphic and Tectonic Framework of the DeSoto Canyon and Lloyd Ridge Protraction Areas, Northeastern Deep Gulf of Mexico: Implications for the Petroleum System and Potential Play Types

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Abstract

The deep water northeastern Gulf of Mexico reflects one of the last frontier exploration areas in the U.S. Gulf. Analysis of 5860 km of 2-D seismic data over the deepwater DeSoto Canyon and Lloyd Ridge protraction areas allows us to evaluate the stratigraphic and tectonic framework of the area and relate that history to the petroleum system and potential play types.

The stratigraphic framework of the study area is divided into five informal stratigraphic units. Each of them contains unique lithologies, stacking patterns and depocenter locations. The stratigraphic units are: (1) Middle Jurassic salt; (2) Upper Jurassic through lower Oligocene carbonates, including the Early Cretaceous carbonate platform; (3) upper Oligocene through middle Miocene clastic submarine fans within a base-of-slope depocenter; (4) upper Miocene progradation of the Mississippi fan within a slope depocenter; (5) Pliocene to present high sediment accumulation rate section within a base-of-slope and basinal depocenter.

The tectonic history of the area is divided into six different time units, based on the type, amount and rate of tectonic activity: (1) Late Triassic through Late Jurassic: rifting, (2) Early Cretaceous: basin subsidence, (3) Late Cretaceous through early Miocene: gravity-driven, extensional-contractional system related to the Early Cretaceous carbonate platform, (4) middle Miocene: tectonic quiescence, (5) late Miocene: contractional system linked to up-dip extension and allochthonous salt deformation to the northwest, (6) Pliocene to present: minor salt diapirism.

The petroleum system in the area involves the complex relationship between reservoir rocks, seal rocks, trap formation and evolution, salt history, source rocks, overburden rocks and petroleum generation, migration and accumulation history. The source rocks in the area are interpreted to be Oxfordian, Tithonian, Cenomanian, Turonian, and lower Eocene. The exact nature of the potential source rocks is unknown as no wells penetrate them in the study area. However, several petroleum seeps are located in the study area, signifying the presence of mature source rocks.

Six play types are defined in the study area. They are: (1) Mesozoic structural play, (2) carbonate slope apron play, (3) middle Oligocene structural play, (4) post-middle Oligocene onlap play, (5) post-middle Oligocene structural-stratigraphic play, (6) shallow salt play. Each of these play types reflects discrete phases of the structural and stratigraphic evolution of the area.

Economic issues related to production from this frontier province are heavily affected by ultra-deep water depths, lack of production infrastructure, oil quality issues, reservoir quality and potential field size.

The Deep Water Gulf of Mexico Petroleum System: Insights from Piston Coring, Defining Seepage, Anomalies, and Background*

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Abstract

In the early days of Gulf of Mexico piston coring, locations were chosen on a grid basis or selected from loose 2D seismic surveys. Such locations resulted in some seepage "hits," but the majority had either a background signature or an "anomalous" value that was between a true visible seep and background (using fluorescence intensity and unresolved complex mixture content). A scale based on these early data identified anything <5,000-10,000 fluorescence units as background, and those values >10,000 were classified as anomalies to seepage depending on individual company interpretations.

With the advent of 3D surveys, it is easier to locate seepage-related seabed features using seafloor amplitude extractions related to migration conduits, such as faults associated with shallow salt features or deep-seated faults. As seepage sites are now better defined and as we have an extensive geochemical database, the old scale for background versus anomaly versus seepage has changed. By correlating true seepage to reservoired oil, most "anomalies" are not related to seepage or to the reservoired oils, and therefore, are not related to the subsurface petroleum system. The biomarker signatures can be used to define source origins, and when merged with regional understanding of source rocks in the greater Gulf of Mexico basin, a deep water source model can be derived. A 2D TemisPack model confirms the seepage results based on a deep water source rock model placing the primary source centered on the Tithonian and possible secondary source rocks at the Mid-Cretaceous Unconformity (MCU) and Oxfordian levels.

Based on oil-to-seep correlations, we can demonstrate:

1. That most piston cores <30,000 fluorescence represent background, 30,000-50,000 are low confidence anomalies, 50,000-100,000 are high confidence anomalies, and >100,000 are truthable seepage.
2. Biomarker signatures of most piston core extracts having <50,000 fluorescence do not correlate to the reservoired oils; however, the number of cores that may correlate to seepage varies regionally. Fewer piston core extracts correlate to seepage in the eastern and central Gulf of Mexico, whereas more extracts correlate to seepage in the western Gulf of Mexico in the 30,000-50,000 fluorescence range. The effects of recent organic matter contamination also differ in other basins, but its effects remain the same, just the thresholds for truthing the extracts are different.
3. Geographical differences exist.
4. A pervasive background biomarker signature is present across the Gulf of Mexico, related to either river discharge sediments containing extractable oil and/or organic matter, or possible sediment dewatering carrying an oil-like signature, unrelated to the subsurface petroleum system.
5. There is a distinct pattern related to the Mississippi Fan. The "background signatures" appear to contain real oil, but do not correlate to the active true seepage.

Using a rigorous approach when interpreting the detailed geochemical data from the piston cores, the "clean" seepage shows a regional trend that can be used to infer source rock type across the deep water Gulf of Mexico. In areas where clastic sourcing is prominent, lower sulfur oils are predicted, whereas in areas dominated by carbonate signatures, higher sulfur oils will be present.

The Depositional Regime on the Abyssal Plain of the Congo Fan in Angola

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Abstract

The Miocene channel play of offshore Angola contains the recent giant discoveries of Girassol, Dahlia, etc. From recent 3D surveys that extend across the salt front onto the abyssal plain in the Outer Congo Fan, it can be seen that this play can now be continued out into theultra-deep water into a new highly prospective frontier area. This presentation covers this area's prospectivity and the use of the models generated here in the salt province.

The Congo Fan of Angola shows evidence of extensive sand deposition from the Oligocene onwards. This sand deposition extends beyond the current exploration targets in the salt diapir province onto the abyssal plain, an area that has been covered by recent 3D seismic data sets.

By using these data, the morphology of differing styles of sand deposition can be shown in a variety of ways including amplitude extraction, timeslices, opacity, and 3D visualisation. All these methods work well in this area because the strong amplitude/acoustic impedance contrast between sand and shale is combined with the approximately flat-lying nature of the abyssal plain. These factors allow the depositional morphologies to be shown without the influence or bias of interpretation.

In this province of offshore Angola, it can be also demonstrated that the Cretaceous and early Tertiary on the abyssal plain shows little or no seismic evidence of sand deposition. However, this section is a prime candidate to contain mature source rocks, the evidence for which can be demonstrated by the clear 'DHIs' seen in the overlying sands. Micro-faults that act as hydrocarbon migration conduits can be seen on the data.

The abyssal plain is at first sight the ultimate location for the 'subtle' (*i.e.*, stratigraphic) trap; however, closures can also be shown to exist as drapes over basement features and allochthonous salt bodies.

The models generated on the abyssal plain can be applied in the far more heavily structured salt diapir province, to provide an understanding of the channel and fan systems in this area. The multiple DHIs here, combined with numerous sands and four-way dip closures suggest that this is a highly prospective area.

Subsalt Exploration Trap Styles, Walker Ridge and Keathley Canyon Areas, Deep Water Gulf of Mexico

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Abstract

We describe the exploration plays associated with the salt nappe, canopy, and massif systems of Walker Ridge and Keathley Canyon areas in the deep water Gulf of Mexico. Depth imaging of 3D seismic allows definition of the salt emplacement and deformation history, and the associated subsalt trap styles.

Salt emplacement in the region follows a simple history: relatively evenly spaced inferred paleo salt stocks have fed salt canopy, nappe, and massif systems. In this region, salt is emanating directly from the Jurassic Louan layer. Mapping of the salt allows division of the present–day salt masses into discrete salt "cells." Emplacement and extrusion occurred in a series of low-angle and high-angle surfaces, dominantly lateral in the canopy and nappe systems, and dominantly vertical in the massif system.

Subsalt structural traps are divided into three major types, from deepest to shallowest: (1) Anticlinal salt–cored folds of Mesozoic and Paleogene strata; (2) Structural inversions ("turtles") of Paleogene and Neogene strata; and (3) Counterregional dip and truncation of Neogene strata against the vertical salt emplacement to lateral salt emplacement transition. Mesozoic anticlines are located basinward of a regional low in the Middle Cretaceous sequence boundary. These structures are fully detached from the superjacent lateral salt masses. These structures are on–trend with recent significant discoveries in more shallow waters. Structural inversions are associated with paleo salt stocks. Salt truncation traps are more shallow and offset from the crest of the inversion structures. Definition of salt "cells" allows an understanding of the development of each structure in the trend, which may imply subtle differences in structural timing and trap competency prior to hydrocarbon emplacement.

One Sea Level Fall and Four Different Gas Plays: The Gulf of Cadiz Basin, SW Spain

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Abstract

The small (2500 km^2) Gulf of Cadiz basin is located offshore in southwestern Spain, in the most western segment of a marine foreland basin, which has a passive margin to the north (Iberian craton) and a fold and thrust belt to the south (Betic ridge). The Messinian sea level fall has generated three distinct but synchronous turbidite systems in the basin. The creation of three distinct systems is a result of intra- and extra-basinal controls on deep-water reservoir development. The greatest distance along the basin floor between the most separated systems is no greater than 80 km. Nine biogenic gas fields have been discovered in these turbidite systems, with recoverable reserves of 140 BCF.

In addition to the turbidites, there is another type of deep-water deposit in the Gulf of Cadiz area, contourites. The contourites have been created by the bottom current that spills from the Mediterranean Sea into the Atlantic Ocean. Exploration possibilities in the contourite section have yet to be established.

The Petroleum System of the Western Atwater Foldbelt in the Ultra Deep Water Gulf of Mexico

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Abstract

Recent major discoveries at Mad Dog, Atlantis, and Neptune have demonstrated a working petroleum system in the western Atwater fold belt (WAFB). Understanding the nature and scale of the petroleum system is important in determining an appraisal strategy for the discoveries and for pursuing other exploration opportunities.

The source interval in the western Atwater fold belt is interpreted to be Upper Jurassic to Lower Cretaceous carbonates and marls. Hydrocarbon generation and migration began in the Upper Miocene and continues to present day. Hydrocarbon reaches the structural traps by a combination of vertical and carrier bed migration.

The traps in the western Atwater fold belt are very large, salt-cored, compressional anticlines cut by both normal and reverse faults. These structures began to form in the upper Miocene and growth continued through the Pliocene. Erosion of the growing structures removed varying amounts of the Miocene section. There is generally less erosion to the southwest and increasing depth of erosion to the northeast.

The reservoir rocks in the western Atwater fold belt are lower and middle Miocene submarine fan lobes deposited at or near the base of slope. Pre-existing structural and depositional topography controlled sand deposition. The fan lobes display a compensational stacking pattern and the reservoir sands are interpreted to be amalgamated and layered sheet sands. Interbedded Miocene shales seal the reservoirs.

Hydrocarbon Systems—Adding Structural Evolution to the Equation

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Abstract

This paper outlines new techniques developed to enable the hydrocarbon system to be fully integrated with the structure model and its evolution through time. The approach was developed to tackle hydrocarbon system problems in complex structural areas where inversion, salt tectonics, or thrust faulting has lead to complex changes in the 3D fairways through time. The technique provides the ability to identify and assess risk in hydrocarbon system models and to generate multiple scenarios. This provides improved input into 2D and 3D basin modeling and allows the key system components to be integrated through depositional stages, faulting and folding and migration.

Using 3D interpretations, a validated back-stripped model provides the basis for modeling sediment pathway and fluid migration fairways at each time step. As the model is run forwards in time, sediment accommodation space and sediment transfer analysis is carried out. This analysis is then integrated with the depositional model. Sub basin spillways, stacking and migration of depocenters can be identified. Using input from basin modeling to identify kitchen areas and timing the migration pathways, fluid focusing and drainage cell analysis can be carried out. Models for fault seal / non-seal, fairways through channels, and compartmentalization can be investigated.

This analysis can then be used to develop and condition appropriate detailed 2 or 3D basin models or applied directly to technical and commercial decision making in exploration. This approach has been successfully applied to projects in the North Sea, deep water Gulf of Mexico, Central and South America, North Africa, and the Atlantic margin. In these areas it has demonstrated clear benefit in significantly reducing work cycle times and in providing technical results that are significantly different from the conventional approaches which have not included the effect of lateral displacements through time during structural evolution.

The Northern Angolan Margin Imaged by Wide Angle Seismic Data

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Abstract

Wide angle seismic data collected on land in Northern Angola during the March-April 2000 Zaiango seismic experiment provide the first detailed image to date of the whole crust down to the upper mantle on the Northern Angolan margin.

Travel times of P-wave refracted arrivals and prominent crustal and mantle reflectors observed to offsets of over 200 km were used to model a crust/mantle boundary, which beneath the continent rises in an oceanward direction, from 40 km to 25 km. In the center of the line, where the crust thins most rapidly, a high velocity body has been interpreted at the base of the crust, reaching some 8 km in thickness. This higher velocity body is thought to represent an area of localized magmatic underplating related to the opening of the South Atlantic and to the Cenomanian volcanism in Angola, as well as the late uplift of the mainland, which may have deep rooted causes.

Seafloor Expression of Fluid and Gas Expulsion from Deep Petroleum Systems, Continental Slope of the Northern Gulf of Mexico

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Abstract

Intense faulting in the northern Gulf of Mexico slope province results from complex interactions between subsurface salt and the deposition of large volumes of sediment. Many of these faults provide pathways for subsurface fluids and gases to migrate from deep petroleum-generating zones to the modern seafloor. These migration pathways are concentrated along the margins of intraslope basins where they are directed by a spectrum of salt geometries. Both geological and biological responses are highly variable and dependent on rate of delivery as well as on fluid and gas composition. Qualitatively, rapid expulsions of gas-charged fluids (including fluidized sediment) result in the deposition of sediment sheets or, mud volcanoes. Both products of rapid expulsion vary greatly in scale. The sheet-like flows may be localized or extend over many square kilometers of the slope while mud volcanoes vary from < 1 m to several km in diameter. Hydrocarbons associated with rapid flux systems reflect little biodegradation during migration. Sediment samples from these seafloor expulsion areas frequently contain hydrocarbons that are remarkably similar to those that are produced from the parent deep subsurface reservoirs that are directly connected to the surface by faults. High accumulation rates, thin depositional units, and limited hydrocarbon storage capacity characterize sediments of rapid flux systems. Lucinid-vesycomyid clams and bacterial mats are the chemosynthetic communities that dominate in these settings.

At the other end of the flux rate spectrum, slow hydrocarbon seepage results in lithification and mineralization of the seafloor. Microbial utilization of hydrocarbons promotes the precipitation of ^{13}C-depleted Ca-Mg carbonates as by-products. These products occur over the full depth range of the slope. Mounded carbonates can have relief of up to 30m, but mounds of 5-10m relief are most common. Mound-building carbonates represent mixed mineral phases of aragonite, Mg-calcite, and dolomite with Mg-calcite being the most common. Barite is another product that is precipitated from mineral-rich fluids that arrive at the seafloor in low-to-moderate seep rate settings. Hydrocarbons analyzed from these slow-flux settings are highly biodegraded and chemosynthetic organisms are generally limited to bacterial mats.

Below water depth of approximately 500 m, intermediate flux settings seem best exemplified by areas where gas hydrates occur at or very near the seafloor. These environments display considerable variability with regard to surficial geology and on a local scale have elements of both rapid and slow flux. However, this dynamic setting apparently has a constant supply of hydrocarbons to promote gas hydrate formation at the seafloor even though oceanic temperature variation (primarily on the upper slope) cause periodic shallow gas hydrate decomposition. In the northern Gulf, gas hydrates contain both thermogenic and biogenic gas. The presence of these deposits provides the unique set of conditions necessary to sustain dense and diverse chemosynthetic communities.

The cross-slope variability of seafloor response to fluid and gas expulsion is not well known. However, present data indicate that the expulsion process is highly influenced by migration pathways dictated by salt geometries that change downslope from isolated salt masses to canopy structures to nappes.

Mesozoic Carbonate Petroleum Systems in the Northeastern Gulf of Mexico Area

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Abstract

Jurassic, Cretaceous, and Miocene deposits are productive of hydrocarbons in the Outer Continental Shelf (OCS) area of the northeastern Gulf of Mexico. Based on regional studies of the onshore and offshore shelfal areas, Upper Jurassic and Lower Cretaceous carbonates are projected as viable petroleum reservoirs in the continental slope areas of the northeastern Gulf of Mexico.

The primary petroleum source rocks for these Mesozoic petroleum reservoirs are believed to be Oxfordian to Kimmeridgian carbonates and Aptian to Albian carbonates and shales. Tithonian shales and carbonates are effective source rocks in Mexico and therefore may also have source potential in the OCS area. The Upper Jurassic source beds are postulated to be natural gas and condensate prone in the OCS area of the northeastern Gulf of Mexico, while the Lower Cretaceous source beds are believed to be oil prone. The natural gas and condensate produced from the Lower Cretaceous (Aptian) James Limestone in the OCS shelfal area is speculated to be sourced from Upper Jurassic (Smackover) carbonates, and the oil produced from Cretaceous (Albian and Cenomanian) Washita carbonates in the OCS shelfal area is believed to be sourced from Lower Cretaceous (post-James) carbonates and shales.

The principal carbonate petroleum reservoirs in the continental slope areas of the northeastern Gulf of Mexico are postulated to be Upper Jurassic deep-water microbial buildups (boundstones) developed on the outer portion of a carbonate ramp. Lower Cretaceous rudist reef rudstones and boundstones and slope carbonate deposits comprised of forereef debris rudstones and shelf-derived grainstones are believed also to have high reservoir potential in this area. Such deeper water deposits have been observed from seismic reflection profiles located seaward of the Lower Cretaceous rimmed shelf margin. Diagenetic studies of the Washita carbonate reservoirs in the OCS Main Pass Block 253 Field indicate that these reservoirs have been subjected to favorable diagenetic processes of dolomitization, dissolution and karstification associated with repeated exposure of the Cretaceous shelf margin.

Seismic reflection profiles indicate the presence of salt-related structures and paleotopographic basement features in the northeastern Gulf of Mexico. Petroleum traps in this region, therefore, are postulated to be combination traps

involving favorable stratigraphic relationships and salt tectonics. The timing of hydrocarbon generation, expulsion, migration and entrapment appears favorable for petroleum accumulation.

Therefore, the continental slope areas of the northeastern Gulf of Mexico appear to have high potential for successful hydrocarbon exploration and development.

Phase Changes: A Major Aspect of Deep Water Hydrocarbon Migration

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Abstract

Hydrocarbon phase separation is a pervasive aspect of deep-water petroleum migration. Major oil fields in the deep water Gulf of Mexico are found at subsurface depths coinciding with significant changes in the solubility of oil in gas—suggesting that oil and gas phase separation is a pervasive step in petroleum migration. Additionally, changes in the solubility of methane in water coincide with the depth of gas reservoirs—suggesting that gas exsolving from water is also a process to consider in hydrocarbon migration.

The solubility of oil in gas is calculated from Price's experimental data and plotted versus depth. Increasing temperature and pressure with depth increases the solubility of oil in gas and it eventually becomes asymptotic, leading to the two becoming cosoluble. Vertically migrating hydrocarbons are most likely to phase separate at this depth. The importance of this depth of phase separation cannot be overstated as the largest fields are found proximally above this depth. Generally, as the magnitude of the change in solubility increases, the accumulation size also increases. Conversely, no commercial pays are found beneath the depth where oil and gas are cosoluble (an economic basement).

The solubility of methane in water is calculated using Haas' program and when plotted versus depth also reveals that major gas reservoirs are commonly found at the same depth where vertically migrating water would experience an abrupt decrease in methane solubility. Results from onshore Gulf of Mexico wells confirm methane saturation at high temperature and pressure and these waters would exsolve gas if the water migrated vertically.

The solubility versus pay relationship is an improvement over the existing pressure versus pay relationship, and, this important new step in the hydrocarbon migration process, fortunately, can be modeled ahead of the bit, thus leading to the development of a new exploration strategy.

Facies Comparison from Bank Margin to Deep Water Basin: Golden Lane Carbonate Depositional System, Southern Gulf of Mexico

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Abstract

Located in the southern Gulf of Mexico, the Golden Lane area comprises a complete carbonate facies assemblage, from lagoon interior and bank margins to slope and basin talus deposits. Using an integrated approach, we have analyzed the depositional processes that directly have influenced the accumulation of reservoir rocks in the Golden Lane area. Comparison of two deep wells that have penetrated into the basement, Atun-502 and Triton-1, has revealed important information regarding the variations of depositional environment in the study area. Cores from the Atun-502 are composed mainly of grainstone and some wackestone and packstone, indicating a back-reef, post-reef, or lagoon environment. The Triton-1 well has been drilled on the lower slope of the Golden Lane carbonate system, to the Tamabra Formation, in a setting similar to slope-rise deposits in a siliciclastic environment. Large intraclasts, rock fragments, pellets, pelloids, and bioclasts characterize the Tamabra in Triton-1; the rocks contain a significant amount of matrix, evidence of talus facies. Understanding the reef to slope facies difference is important in order to define reservoir models for the oil fields in the Golden Lane area.

Another important observation is that cyclic features are more remarkable in the Triton-1 well than the Atun-502 well. One explanation is that the deposition of deep basin carbonate talus was significantly influenced by different modes of sediment input due to the variation of sea-level cycles on the bank margins. This study may provide additional information on the response of carbonate system to sea level variations.

The Past and Future Exploration Potential of the Deep Water Gulf of Mexico

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Abstract

On October 16, 1975, Placid spudded the first deep water wildcat well in Mississippi Canyon block 113 initiating the exploration of the deep water Gulf of Mexico. Twenty-five years and 392 wildcats later, 121 discoveries have been made yielding an estimated ultimate recovery (EUR) of 10.6 billion barrels of oil equivalent (BOE) reserves. Fields such as Auger, Mars/Ursa, Crazy Horse, and Mad Dog demonstrate that field reserves of 300 million to 1 BBOE are possible and that significant potential (10–20 BBOE) remains for the next generation of drilling in 2001 and beyond.

An accurate assessment of risk and reserves is critical for the prudent investment of future plays in the Deepwater Gulf of Mexico. To achieve this, an understanding of drilled wells and trends is necessary. For this project, all wildcats in water depths greater than 400 meters (1,300 feet) were grouped into a specific tectonic setting, stratigraphic age, and trap style, which ensured meaningful statistical analyses. Tectonic settings included basins (extensional), fold belts (compressional), Sigsbee plain, and subsalt. The major stratigraphic ages are Pleistocene, Pliocene, and Miocene, and the four possible trap styles are 4-way anticline, 3-way faulted structure, salt/shale truncation, and stratigraphic.

At present, 88% of the wells have tested structures in basins, resulting in a 32% success rate, an average of 68 MMBOE/discovery totaling 7.5 BBOE reserves. The remaining 12% are in the subsalt (26 wells) and foldbelt (19 wells) tectonic settings. These have success rates of 27% and 26%, respectively. The subsalt has yielded 2 BBOE, averaging 285 MMBOE per discovery. The foldbelt has contributed 1.1 BBOE with an average of 230 MMBOE per discovery.

The first half of 2001 has already added 500 MMBOE reserves and should total 1 BBOE by year-end. This will be the fourth year in a row that the one billion barrel mark of added reserves has been achieved. Two world records have also been set. Unocal set a world record for water depth by drilling the Trident prospect in Alaminos Canyon block 903 in 9,687 feet of water. Chevron set a world record for total depth drilled with the Poseidon prospect in Mississippi Canyon block 727, which drilled to 29,750 feet. Continued advances in deepwater drilling, development, and production technology and seismic imaging will allow industry to tap the vast potential of the fold belt and subsalt areas of the deepwater Gulf of Mexico.

Sea Floor Vents, Seeps, and Gas Hydrate: Relation to Flux Rate from the Deep Gulf of Mexico Petroleum System

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Abstract

A deep, hot subsurface petroleum system in the Green Canyon area of the Gulf slope has generated oil and gas synchronously with salt deformation and fault activation, producing vertical migration conduits that charge traps in the subsurface. Trapping efficiency is poor. Much oil and gas is lost to venting and seepage at the sea floor. Sea floor vent and seep environments show hydrocarbon flux that ranges from rapid venting to slow seepage, affecting hydrocarbon geochemistry and gas hydrate abundance. Active mud volcanoes that vent oil and gas are the high flux end-member. Oil and gas rapidly bypass the sediment and enter the water column. The oil from the active vent sites shows only limited bacterial oxidation. Venting is episodic and may cease altogether, and warm brines may be present, potentially destabilizing gas hydrate. It appears that gas hydrate is only indirectly associated with high flux mud volcanoes. Massive gas hydrate is most often found at sites of moderate flux. Gas hydrate is associated with smaller but steady vents of relatively unaltered thermogenic gas, chemosynthetic communities, and authigenic carbonate rock. Oil-related structure II gas hydrate is most abundant. Oil and free gas in sediment are bacterially oxidized in moderate flux environments, leading to accumulation of abundant authigenic carbonate rock and to H_2S, favoring complex chemosynthetic communities. Exposed gas hydrate is transiently unstable because of changes in seawater temperature, but this is a thin-skin process and more deeply buried gas hydrate appears to be stable and accumulating. Mineralized seep sites with low hydrocarbon flux do not appear to be important with respect to gas hydrate accumulation.

On the Importance of Understanding Why Deep Water is Deep—a West Shetland Perspective

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Abstract

Considerable crustal stretching is required to create a basin that has water depths in excess of 500m. The character, magnitude, and timing of crustal stretching has important implications for the petroleum system particularly with respect to basin structuring, heat flow and source-rock distribution, quality, and maturity. Nowhere does understanding the crustal-stretching history have more importance than in deep water basins, such as the West Shetland basin-system, where the source rocks were deposited before the main rift-events.

One of our challenges in the West Shetland basin-system has been to produce a viable tectonic model that can explain the apparent incompatibility between the present-day bathymetry and the observed basin architecture. The Faeroe-Shetland Channel is a prominent northeast-southwest trending bathymetric trough situated between the Shetland and Faeroe islands. Water depths in the axis of the channel are in excess of 1700 m. The form of the channel and the underlying geology of the Faeroe-Shetland basin system are shown in. The crust under the channel is significantly thinned the computed depth to Moho being as high as -15 km. The bathymetric low and its corresponding Moho high are, however, significantly offset with respect to the main depositional axis of the Faeroe-Shetland basin system. The depth to top basement in the axis of the basin system is as low as -13 km. The combined Cretaceous and Paleocene section in the axis of the basin is over 10 km. This section thins dramatically towards the high ridges that frame the basin where total thickness of Cretaceous and Paleocene rocks can approach 0 km.

The Faeroe-Shetland basin system was at or very close to sea level at the end of the Paleocene as evidenced by subaerial lavas in the Upper Series of the Faeroe Plateau basalts and marginal marine rocks of the earliest Eocene Balder Formation. The prominent bathymetric trough—Faeroe-Shetland channel—is a post-Paleocene feature. It is somewhat of a paradox, therefore, that there are no recognisable post-Paleocene faults of a magnitude to create a trough that has water depths in excess of 1700 m or to generate crustal thinning to a point at which the Moho is now at only -15 km. Stretching of the lithosphere under the trough is markedly heterogeneous—extension in the upper crust is significantly lower than the observed extension in the lower crust and mantle lithosphere.

Anomalous subsidence patterns and heterogeneous lithospheric extension are common observations at continental margins. Depth-dependent stretching and the associated process of mantle-exhumation are known to occur at continental margins in association with sea floor spreading. The Faeroe-Shetland channel has developed after the opening of the North Atlantic. It would be tempting to speculate that depth-dependent stretching, in association with the opening of the North Atlantic, created the Faeroe-Shetland Channel. The trough is, however, linear and at a high angle to the continent-ocean transition zone to the east of the Faeroe Islands. For depth dependent stretching to have caused the observed anomalous subsidence, there must have been selective migration of mantle lithosphere and lower crust from beneath the channel during breakup northward toward the developing North Atlantic Ocean.

Depth-dependent stretching is a process associated with sea-floor spreading and thus cannot explain the apparent Mesozoic heterogeneous stretching in the Faeroe-Shetland basin system. “Traditional” methods of basin reconstruction (flexural unloading and decompaction; removal of fault-heaves) using “traditional” interpretations of the basin

geology are unable to satisfactorily backstrip and/or forward-model the interpreted geology. Stretching-factors derived from summing the fault-heaves across the Faeroe-Shetland basin system simply do not match the stretching-factors derived from subsidence calculations or the stretching-factors derived from measurements of crustal-thinning. This prompts one to believe that either something is amiss with the reconstruction approach, or that the input interpretation and/or our assumptions about the basin history are flawed.

Triassic/Early Jurassic deformation in Western Europe was partitioned into a broad rift-system that linked from continental Europe, through the North Sea, and northwards into the East Greenland/Norway system. This rift-system also extended along the western margin of Ireland and the UK where it reactivated many older post-Caledonian basinal elements. It is important to note, however, that the subsequent Middle to Late Jurassic rift-system, so prominent in mid-Norway and the North Sea, did not extend in any substantial way through the Faeroe Shetland basin-system. Plate reconstructions, made using the program PLATES, suggest that Jurassic rifting was partitioned principally into a system that extended from the Arctic Ocean, through the Norwegian Sea, the North Sea and across Continental Europe. According to the plate reconstructions, the main phase of rifting between Greenland and the Faeroes/UK did not begin until the mid-Cretaceous, ca. 120Ma.

The initial motion between Greenland and the Faeroes/UK (ca. 120Ma–95Ma) was oblique to the trends of earlier basins in the Faeroe-Shetland basin-system that were more northeast-southwest. Reconstruction strategies must accurately account for the oblique character of the rifting, otherwise anomalously low estimates for fault heave may occur. It is also important to recognise that in oblique-rift settings, very high crustal stretches can occur. In fact, high-stretch numerical forward models can replicate many features (*e.g.*, the form of the ridges that frame the basin, the intra-rift ridges, and the syn- and post-rift stratal stacking patterns) of the observed basin.

A tectonic model is thus emerging for the West Shetland region in which the main rift event responsible for establishing the Faeroe-Shetland basin system as a major sediment depocenter began in the mid-Cretaceous. The stretching direction is initially oblique to earlier basin trends and eventually had a very-high stretch. These observations are of fundamental significance because the magnitude, direction, and timing of rifting ultimately controlled key parameters of the petroleum system. The distribution of source, reservoir and seal rocks and the timing and generation of hydrocarbons with respect to structural development are all a function of the rift history.

The opening between Greenland and the UK changed significantly late in the Cretaceous (~85Ma), as the direction of rifting became more orthogonal to the present plate boundary. This important period of extension in the Faeroe-Shetland basin system continued into the late Paleocene. Many of the main basin elements (*viz.*, Corona ridge, Westray ridge, Flett ridge, and Rona ridge) owed their current “form” to this Paleocene extension that was the precursor to the early Eocene breakup. Following break-up of the North Atlantic in the early Eocene, rapid post-rift basin subsidence, possibly caused by depth-dependent stretching, created a deepwater trough—the Faeroe-Shetland channel—in which water depths are in excess of 1700 m.

Obstacle and Sinks: Effects on Turbidite Flow on Deepwater Continental Margins

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Abstract

Numerical models are used to investigate the effects of bathymetric obstacles and sinks on turbidite flow and sediment deposition. Modeling results suggest that bathymetric obstructions such as salt domes produce a thick sedimentary apron on the landward side of the dome and a heart-shaped thin area over the dome crest. The maximum thickness of sediment is located where the flow impinges on the dome. Seaward-dipping fault scarps accelerate flow and produce local elongate depocenters both landward and seaward of the fault scarp. The depocenter is located seaward of the scarp as flow accelerates over the scarp, and there is no deposition immediately in the hanging wall. Counter-regional faults are very effective barriers to sedimentation and produce an elongate depocenter in the hanging wall of the fault. Oblique counter-regional faults produce an asymmetric depocenter, in which the thickest sediment is located in the opposite direction to the flow deflection. Depressions caused by salt withdrawal are the most effective sediment traps and produce depocenters twice the thickness of those produced by fault scarps or salt domes.

Thrust, Kinematics and Hydrocarbon Migration in the Middle Magdalena Basin, Colombia, South America

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Abstract

Petroleum systems commonly develop in large sedimentary wedges. In Colombia, large sedimentary wedges exist along the Pacific active margin, along the Caribbean right-lateral transcurrent margin, and in the Middle Magdalena Valley basin. The Middle Magdalena basin Neogene sedimentary wedge gently laps onto the Precambrian/Lower Paleozoic metamorphic rocks of the west wall of the Middle Magdalena Valley basin, which is the Central Cordillera. The Central Cordillera is the northern extension of the Andean magmatic arc created by subduction of the Farallon/ Cocos plates. This volcanic arc has been active, certainly during historic and present times.

The end of Mesozoic-initiated subduction parallel to the Upper and Middle Magdalena Valley basins triggers the uplift of the Central and Eastern Cordilleras. The Eastern Cordillera, east of the Middle Magdalena Valley, displays abundant reflection seismic evidence of east to west thrusting involving Tertiary and Cretaceous valley sediments during Late Paleocene-Early Eocene, related to Central Cordillera uplift. Thrusting continues today to the west of the Eastern Cordillera, at a rate of several cm/year. Low-grade deformation associated with thrusting can nucleate folds and lead to fracturing having no lateral movement. Such deformation can create non-steady state complex fluid flow at various scales, by opening and closing migration routes through fracture networks. Higher-grade compressional deformation, such as shortening across the Middle Magdalena Valley associated with the Eastern Cordillera uplift, inverts former extensional features during the Paleocene and middle to late Miocene. This structural inversion is documented in oil fields within the basin such as La Cira-Infantas giant oil field.

Uneven advance of the thrust and deformation front in a vertical and lateral sense adds greater complexity to regional shortening of the Middle Magdalena Valley basin. The advance of the eastern wall (Eastern Cordillera) of the Middle Magdalena Valley basin is not continuous. Portions of the eastern wall advance more rapidly than others as evidenced by the uneven and irregular spacing of Holocene faults. Irregular deformation rates seen on the surface may also apply to the subsurface. From a petroleum system perspective, a sedimentary body less deformed than its neighbors may retain its fluid longer. When local deformation finally occurs, it may be relatively rapid. Fluid expulsion then can be more energetic than in adjacent areas, and a second phase of hydrocarbon migration takes place.

Potential Deep Water Petroleum System, Ivory Coast, West Africa

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Abstract

All of the petroleum accumulations discovered to date in Côte d'Ivoire are along west-northwest to east-southeast trending anticlines bounded by normal faults known as the Lion, Foxtrot, Espoir, and Quebec highs. An analogous positive structural feature, the Grand Lahou high, exists in 1500m+ water depths. Basinward of the Grand Lahou high is the Grand Bassam sub-basin, which may contain rich deep water source rocks and reservoirs.

The oldest known reservoirs are Aptian/Albian clastics, which grade up-section from lacustrine to marginal marine. Later Albian and Cenomanian fluvial and shallow marine sediments form additional reservoirs overlying an unconformity dated at 98 Ma. Slope canyon systems did developed during Coniacian time. Additional deep water clastic reservoirs are deposited in Coniacian, Santonian, Campanian, and Maastrichtian times. Less well-developed slope canyon systems have formed reservoirs during the Miocene.

Gas prone source rocks have been encountered in middle Albian shales. Oil prone source rocks have been encountered in upper Albian marginal marine shales, upper Albian shallow water limestone, and Cenomanian/Turonian shallow marine shales. Oil geochemistry suggests the presence of a fifth source rock, most likely Albian-Aptian lacustrine shale. Oils reservoired in the western part of the basin appear to originate from lacustrine and marine sources, while oils reservoired in the eastern part of the basin are from exclusively marine source rocks.

Future deep water discoveries may be found along the Grand Lahou High or in deeper basinal areas of the Grand Bassam sub-basin. Trap types and reservoirs along the Grand Lahou high would be similar to those found in shallower water along the Lion-Quebec high, consisting of Albian and Cenomanian fluvial and shallow marine sandstones in fault and stratigraphic traps on Albian highs. Other potential accumulations may be found in stratigraphic traps associated with Campanian through Maastrichtian slope canyon systems, which have been identified in shallower water. These same canyon systems feed into the Grand Bassam sub-basin, and may compose slope canyon and basin floor fan sand reservoirs.

Late Mesozoic and Cenozoic Deposystem Evolution in the Eastern Gulf of Mexico: Implications for Hydrocarbon Migration

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Abstract

A preliminary analysis of Mesozoic and Cenozoic deposystems in the eastern Gulf of Mexico, using published regional stratigraphic and depth to basement studies, reveals striking elements of deposystem history and petroleum system architecture. Integration of thirteen regional studies into a single chronostratigraphic framework provides a basis for assessing accumulation rates within eight provisional Late Mesozoic second-order depositional sequences and eight Cenozoic second-order depositional sequences spanning the interval 165 Ma to the present.

Interval accumulation rate mapping reveals that major deposystems shifted in response to the changing tectonic setting of the Gulf basin. The evolving deposystems reflect changes in sequence architecture corresponding to evolution from a dynamic environment of salt tectonics and hot mobile crust in the youthful Gulf basin to cool thermally stable modern crust where gravity driven depositional patterns dominate. Shifting depocenters throughout this period differentially loaded and compacted underlying sediments, thus modifying pressure gradients that influence the lateral migration pathways of hydrocarbons. Analysis of differential deposystem loading predicts that hydrocarbon migration paths locally converge within the original Federal lease sale 181 area, principally because Late Cretaceous strata in the area are relatively thin compared to adjacent areas. While perceived hydrocarbon risk is therefore diminished, low accumulation rates for most sequences suggest that reservoir risk in a given vertical section is high. The search for productive reservoir in the area should therefore focus on specific parts of the section immediately above or below a condensed Middle Cretaceous Sequence Boundary (MCSB) interval that exhibit accumulation rates higher than the regional average. Accordingly, the late Albian-early Cenomanian (Paluxy sequence) and the middle to late Miocene (upper Miocene sequence) are preferred candidates for exploration.

Capillary Seals as a Cause of Pressure Compartmentation in Sedimentary Basins

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Abstract

A new hypothesis that pressure compartmentation in basins can be caused by capillary seals is presented and discussed. Capillary seals form when a non-wetting fluid phase is generated within or introduced into grain-size layered sediments that are fine-grained enough that gravitational separation of the phases does not occur. Experiments show that such seals can be formed in the laboratory. These seals have many important implications: The changes in basin permeability that allow fluid overpressuring may occur when non-wetting phases are generated in the basin (CO_2 or hydrocarbon). Basin seals can be dynamic; they can move through the sediment column. Porosity profiles reflect such movement. Hydrocarbons and water may follow the trajectory of seal rupture and move along the same migration routes. The flow of both water and hydrocarbons may be directed to areas where the top of overpressure is covered by the least sediments. We have not proven the capillary seal hypothesis, but diverse evidence supports it and it has important implications.

Source Rock Characterization and Maturity Modelling of the Coastal and Deep Offshore Basins of Tanzania

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Abstract

The Coastal basin of Tanzania is a known petroliferous area. Hydrocarbons occur at the surface on Pemba Island and the Tanzania mainland and shows of oil and accumulations of gas have been proved in several offshore and coastal island wells. These occurrences display varying geochemical characteristics pointing to the existence of several active petroleum systems. The Mafia deep offshore basin (MDOB) of southern Tanzania occupies an area of some 75,000 km^2 developed between the Coastal basin and the Davie fracture zone some 200 km to the east. This undrilled frontier basin is interpreted to be the generative area for the hydrocarbon occurrences recorded in the Coastal Basin.

To assess further the prospective framework of the MDOB, a study of some 1700 source characterization analyses from wells in the Coastal basin of Tanzania was undertaken together with a critical review of the geochemical characteristics of hydrocarbon shows and reservoir fluids. The study recognized the occurrence of four oil-prone source formations:

1. Middle Eocene (mixed Type II/III kerogen)
2. Upper Cretaceous (mixed Type II/III kerogen)
3. Middle Jurassic (mixed Type II/III kerogen)
4. Lower Jurassic (Younger Karroo, predominantly Type I/II kerogen).

Seismic data indicate that Upper Cretaceous shales are regionally developed throughout the deep-water area and that Younger Karroo likely source bearing half-grabens are present in the subcrop over much of the MDOB. In addition to these oil-prone sources, Lower Cretaceous and Triassic (Older Karroo) gas-prone source formations are also identified. Data are presented to indicate the source richness and petroleum potential of the various formations.

Maturity modelling and calibration has been undertaken for the following key source-indicative surfaces over the deep offshore area:

1. Base Middle Eocene (for Middle Eocene sources)
2. Mid Cretaceous Unconformity (for Upper Cretaceous sources)
3. Top Karroo (for Middle and Lower Jurassic sources).

The results of the modelling study demonstrate that the middle Eocene and mid-Cretaceous surfaces are presently at oil window levels of maturity, the mid-Cretaceous surface having entered the oil window in the early Miocene. The Top Karroo surface is currently at gas generative or spent levels of maturity. The interpreted maturation history of the principal source formations in the MDOB appears consistent with the pattern of biomarker and isotopic data for the various hydrocarbon occurrences in the Coastal Basin.

Determination of Paleogeography and Depositional Environment Within Phosphate Bearing Remnants of the San Pedro del Gallo Terrane in Northeastern Mexico

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Abstract

Geochemical and sedimentological data obtained from outcrop localities examined during the present study are presented to explain the origin of bedded phosphatic limestones for selected San Pedro del Gallo terrane remnants (SPGTR) occurring southwest of the Walper Megashear in northeastern Mexico. Three "remnants" of the San Pedro del Gallo terrane (SPGT) (lower Oxfordian to upper Hauterivian) are examined, concentrating on the outer bathyal to upper abyssal La Caja Formation (lower Kimmeridgian to upper Tithonian). During the late Tithonian, a worldwide phosphorogenic episode is recorded from deposits occurring along the western margin of continental masses. In Mexico, a study of the upper Tithonian phosphorite interval (Unit D; Mazapil and Iturbide remnants) has revealed the presence of five phosphatic zones (MPL-1 to MPL-5) from the Mazapil remnant, and three phosphatic zones from the Iturbide remnant (IPL-3 to IPL-5). In addition, three "phosphatic realms" (PR-1, PR-2, and PR-3) occurring in the upper portion of the La Caja Formation within the Mazapil and Iturbide remnants of the SPGT have been assigned. In addition to the PR-zones, the sequence of phosphatic limestone deposition within Unit D from the Mazapil and Iturbide remnants displays geochemical signatures resulting in the identification of three phases or pulses of phosphatic limestone turbidite activity. The paleogeographic configuration of continental masses in the Northern Hemisphere and corresponding paleocurrent configurations, and the depth at which these currents encounter the zone of photosynthesis, along with the effects of nutrient-rich upwelling waters, are proposed as primary limiting factors to the initiation and subsequent termination of bedded phosphorite formation within the San Pedro del Gallo basin.

SEAMAGIC or How to SAMBA in South East Asia: Reservoir and Petroleum System Controls, a Tectonic Recompilation and Prospectivity Analysis

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Abstract

Remarkable correlations between gravity imagery and reservoir distribution have been documented in basins offshore Brasil and West Africa in a simple passive margin setting. The present group has tackled Southeast Asia, and its much more complicated plate history, placing the petroliferous basins in a clearer tectonic framework. We used a GIS environment to enable faster and more precise interpretation methods and digital presentation of results. First we correlated published geological features to gravity and magnetic anomalies displayed as geotiffs (geo-referenced images). We reinterpreted, realigned and extrapolated even long-recognized features not previously imaged in their entirety, due to inadequate data coverages. We refined the location and extents of many first-order tectonic features through their gravity/magnetic signatures, including the Red River, Three Pagodas and other faults, the outlines of most of the Tertiary basins, and various discovery trends.

Our results contrast examples from the Campos and Lower Congo basins (showing sediment distribution controls by basement faulting and salt-involved compression respectively) with both extensional and compressional regimes in Southeast Asia. In each region, potential field signatures suggested relationships that explained reservoir distribution or controls on petroleum systems. While mapping terrane boundaries, we also reinterpreted extents of continental, oceanic and proto-oceanic crust and their depths, with natural consequences for hydrocarbon maturation modeling. Side benefits of a GIS approach are: (1) the ease with which multiple data sets from participants can be integrated and updated; and, (2) improved corporate memory as the project evolves.

Gas Capillary Inhibition to Oil Production

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Abstract

In a sand reservoir, grain-size variations and the presence of two separate phases can result in capillary barriers that impair oil production. We calculate the effect capillary barriers could have on the cumulative oil production and derive a formula for the time at which the capillary loss of production will reach 20%. Our calculations replace the traditional Darcy's law with a plastic flow law that prohibits flow unless the driving pressure gradient is larger than a specified minimum. The minimum pressure gradient depends on reservoir conditions that can be controlled to some degree.

Subsalt Trap Archetype Classification: A Diagnostic Tool for Predicting and Prioritizing Gulf of Mexico Subsalt Traps

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Abstract

The accurate assessment of trap attributes remains a primary determinant of subsalt exploration success. Gulf of Mexico 3D seismic datasets, subsalt well results, and kinematic models have been integrated into a calibrated methodology for assessing subsalt trap geometry and prospectivity. Subsalt traps can be grouped into genetically distinct archetype families, a classification that reveals the predictable influence of common salt styles on specific trap attributes. The archetype families are qualitatively ranked for exploration value according to their inherent trap risks, forming a basis for evaluating the prospectivity of even poorly imaged subsalt objectives.

Within the complex salt systems of the northern Gulf of Mexico, subsalt stratal geometries are highly variable. Narrow, three-way *ribbon truncation closures* and steep stratal dips pose generic exploration risks, while trap prospectivity may be greatly improved where subsalt strata have been counter-rotated, inverted, and/or downwardly flexed. Structural elements that enhance or destroy subsalt trap viability evolve with the deformation of ubiquitous, deeper allochthonous and autochthonous salt. The concept of *vertical linkage* describes this systematic relationship between deep salt movement and the magnitude and mode of subsalt trap deformation. Empirical observations and kinematic models demonstrate that vertical linkage is, in turn, dictated by local salt root geometry. Three kinematically distinct subsalt root types are recognized: *autochthonous salt roots, fore-ramping allochthonous salt roots,* and *back-ramping allochthonous salt roots*. Each root style exerts a predictable influence on subsalt stratal geometry, thereby providing explorationists a means of inferring trap attributes that may be obscured by overlying salt.

End-member trap archetypes illustrate frequently occurring subsalt trap styles, and are grouped into four play families: (1) sub-suture traps, (2) autochthon rooted traps, (3) fore-ramping allochthon rooted traps, and (4) back-ramping allochthon rooted traps. Sub-suture traps occur as bilateral stratal truncations against salt base antiforms, and present high-risk objectives having the lowest overall value. In contrast, the top ranked family of autochthon rooted traps includes highly prospective salt cored and inverted subsalt anticlines. The allochthonous fore-ramping and back-ramping trap families fall in between these extremes and are ranked by their generic subsalt fold styles. Fore-ramping roots promote risk-inducing upward stratal flexures, while back-ramping roots yield favorable downward flexures, warranting third and second priority rankings for the respective play families.

Processes Impacting Deep Water, Subsalt, Fold Belt Hydrocarbons

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Abstract

A brief compilation is presented of geologic processes, both subsalt and deep water. The processes include hydrate formation and destruction associated with hydrate stability zones, the evolution of salt-floored basins, the generation of earthquakes and paleofracture zones with associated thermal anomalies, the migration of Louann Salt with associated fracture development and gas expansion/contraction, compressional foldbelt development, subsalt pressure compartment evolution, and major changes in deposition rates from highstand to lowstand during the Quaternary, and probably the entire Neogene. Earthquakes and paleo-fracture zones associated with thermal anomalies, along with hydrates and hydrate stability zones, are suggested as permanent geologic inputs. Deposition rate variability, especially during lowstands, fills in the basin. This infilling creates the various physiographic and depositional provinces from coastal plain to abyssal plain.

A "Healed Slope" Model for the Deposition of Turbidite Reservoirs Applied to Shell's Zia and Oregano Discoveries in the Deep Water Gulf of Mexico

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Abstract

Shell Exploration & Production Company has recently made two smaller-volume discoveries in the deepwater Gulf of Mexico: Zia (Mississippi Canyon 496) in 1998 and Oregano (Garden Banks 559) in 1999. Neither of these discoveries is large enough for Shell to develop using a fixed production facility, but they become profitable if tied back to an existing host platform as a subsea development. An understanding of the depositional environment and reservoir architecture of the main pay sands at Zia and Oregano has been an important component of the detailed development planning that is necessary in order to optimally locate the development wells.

The primary oil-bearing reservoirs at both Oregano and Zia are examples of sands that have been deposited in what has been referred to as a "healing phase" of turbidite deposition (Booth *et al.*, 2000). Elsewhere in the region around the discoveries, the stratigraphic interval in which the pay sands occur is normally a bypass facies assemblage (*e.g.*, Prather *et al.*, 1998), as most of the sand in the vicinity is diverted out into the basins in deeper water. At Oregano and Zia, however, locally unique conditions have resulted in "healing phase" deposition instead. A local topographic indentation or change in slope has formed along the seafloor, possibly in response to salt movement nearby. Turbidite sands transported down from the shelf encounter the break in slope at the edge of the indentation and are deposited as a local area of amalgamated turbidite sheet sands. The area of topographic relief is quickly filled or "healed over" by the deposition of the initial sands and the system transitions back into the bypass mode. Subsequent turbidite sands may be deposited on top of the "healing phase" sheets as amalgamated channel complexes. In the case of both Oregano and Zia, the channel sands cut into the underlying sheet sands and may improve reservoir connectivity. Finally, as the last slight topographic variations are smoothed out, the true bypass system is restored. Younger shale-filled channels that often partially cut into the underlying reservoir and help to trap the accumulation are observed in the 3D seismic data volume.

In turbidite reservoirs formed by this type of process, the proximal end of the amalgamated sheet sand complex is a higher energy depositional setting, in which there is often a predominance of sand-on-sand contacts. This is also the place where the overlying amalgamated channel complexes may cut into the sheet sands beneath, providing many different mechanisms for interconnected sand bodies. The distal end, by contrast, will have a lower overall net-to-gross and interbedded shales that can isolate portions of the reservoir. Understanding these components of the depositional model and their areal relationship to the depth structure of the accumulation is important in planning a successful development.

Transtension Along an Ancient Lineament: Example from the South Caspian Basin

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Abstract

Data from field mapping, seismology, gravimetry, and rock chemistry show the south Caspian oceanic crust to be underthrusting the continental crust of the Eurasian plate to the north and, at the same time, that of the south Caucasian plate to the southwest. Explanation is supposed to come from transtension along a 40 km-wide, ancestral lateral displacement zone whose southern master fault coincides with latitude 40° north. In the Azerbaijan mainland, the 40th parallel shear zone embraces, from east to west, the Pliocene-Quaternary Navaghy pull-apart basin near shore; the S-shaped Sarysou Lake in the Kura River valley; a series of Jurassic calderas in the Lesser Caucasus; and the superimposed Kelbadjar caldera west of the ophiolitic belt. An offshore seismic profile across the 40th parallel reveals a flower structure.

Satellite images of the region between the Black and Caspian seas show the high heat flow-related zone of surficial evaporation striking along 40° N. The associated thermal anomaly results in high fluidity of flows being produced by mud volcanoes in the 40th parallel shear zone. Evidence for the extensional nature of the 40th parallel shear is provided by the 180°-reversal in the direction of tilt of mud volcano feeders and of fold vergence.

The 40th parallel shear appears to be inherited from a pre-existing Precambrian basement structural fabric. Volcanologic studies in the Lesser Caucasus have shown that the shear zone was active in the Paleozoic. Comprehensive analysis of the south Caspian basin is impossible without understanding the role of pre-existing crustal weaknesses in its evolution, architecture and petroleum system.

The Porosity-Depth Pattern Defined by 40 Wells in Eugene Island South Addition, Block 330 Area, and its Relation to Pore Pressure, Fluid Leakage, and Seal Migration

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Abstract

Porosity-depth profiles determined from density logs in numerous wells in the Eugene Island South Addition Block 330 area of the offshore Louisiana Gulf of Mexico show departures from the expected hydrostatic compaction trends at depths ranging from 900 m to 1950 m. At greater depths, porosities may remain constant, increase, or decrease. Although it changes over distances of a few kilometers, the porosity pattern is locally coherent. The cause of porosity departure from the expected compaction related trend (hydrostatic trend) is in all observed cases pore pressures in excess of hydrostatic pressures.

Porosity profiles are plotted and analyzed in detail in 40 area wells. Fluid pressure in these wells can be predicted from porosity because porosity is linearly related to effective stress. The depth at which porosity departs from the hydrostatic trend (the porosity-defined top of overpressure) coincides mostly with the 1.27 Ma transgressive *Helicosphaera sellii* shale that immediately overlies the gas-charged "JD" sand. However, in Block 314, the porosity-defined top of overpressure lies 500 m above the *H. sellii* surface, passing above two sand units and two transgressive shales.

In this paper we derive analytical expressions that were used to interpret porosity profiles and overpressure relationships. One well in Block 314 was analyzed in detail as an example. In this well a seal was developed in the *H. sellii* shale when the shale lay at ~550m depth. When this lithologically fixed seal was gradually buried to 1430m depth, fluid pressures in underlying strata reached 0.8 of lithostatic and the seal began to deform and leak. Continued leakage while the seal was buried to its present depth of 2020m produced an interval of constant porosity (migrating seal compartment) from 1040 to 2020m.

Although other interpretations are admittedly possible, we suggest that the migrating seal compartment formed when hydrocarbon fluids were introduced and capillary barriers developed. Applying the same methods, we identify areas in the Eugene Island South Addition Block 330 area where venting has diminished and areas where it has accelerated. The methods further developed and illustrated could facilitate exploration for higher porosity, more permeable sand reservoirs, address hazards associated with fluid overpressuring, and extract information on the timing and nature of hydrocarbon venting from a new information base: shale porosity profiles.

Economic Potential of the Yucatan Block of Mexico, Guatemala and Belize

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Abstract

The Yucatan block is a rifted continental microplate covering 450,000 sq km in southern Mexico, northern Guatemala, and Belize. The crystalline basement is mantled by a Late Jurassic through Recent carbonate/evaporite platform up to six km thick. The southern margin of the block was affected by Late Cretaceous suturing to the Chortis microplate followed by Miocene to Recent strike slip faulting. Its eastern margin was modified by Paleogene strike-slip against the Cuban Arc Terrane. The Yucatan Block has received very little terrigenous sedimentation since it was isolated from nearby landmasses by the Jurassic separation of North and South America.

There is major hydrocarbon production in Mexico from the area immediately west of theYucatan block in the Reforma trend, Campeche Sound, and the Macuspana basin. Oil has also been found in the Sierra de Chiapas west and south of the block in Guatemala and Mexico. Only one commercial oil accumulation has been found to date on the stable block itself, *i.e.*, Xan Field in Guatemala, while unsuccessful mineral exploration has been limited to the small area of exposed crystalline basement in the Maya Mountains of Belize.

Based on current knowledge, it is the author's opinion that the economic potential of the Yucatan block should not be discounted. Hydrocarbon exploration has been sporadic and generally low-tech, and there is a clear need for high quality regional seismic data to reveal the structural configuration and sedimentary architecture. Among the many geological factors to be understood are:

1. The geometry of Triassic-Jurassic rift structures (horsts and grabens)
2. The location and geometries of possible Jurassic and Cretaceous intraplatform hydrocarbon source basins, potential carbonate buildups, and structural traps within the evaporite/carbonate section
3. Paleo-heatflow as it affected organic maturation
4. The effects within the block of tectonics along its margins (tilting, mass wasting and foreland bulging.)
5. The effects of the Chicxulub K/T astrobleme.

Experimental Investigation of Capillary Blockage of Two Phase Flow in Layered Porous Media

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Abstract

The flow of two fluid phases through a tube filled with layers of sediments of contrasting grain size has been investigated in the laboratory. The gas phase is introduced uniformly into the sediment pore spaces by decompressing CO_2-charged water flowing through the tube. After a brief transition, the flow of both phases is blocked until the pressure across the tube exceeds a threshold equal to the sum of smaller thresholds at each fine layer. The permeability of the fine layers to the flow of both fluid phases is effectively reduced by at least seven orders of magnitude. Capillary forces are responsible for this blockage. The threshold pressure is predicted by Laplace's capillary formula and the temperature dependence of the threshold pressure is that of interfacial tension. The capillary barriers are highly resistive to permanent rupture by faulting or fracturing.

Gulf of Cadiz (Western Spain): Characterized by a Complex Petroleum System

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Abstract

The petroleum system is that series of interrelated processes by which hydrocarbons are generated and migrate to reservoirs from which they can be extracted commercially. The complex geology of the Gulf of Cadiz provides three separate heat sources for thermal maturation, while energetic downslope movement of crustal blocks has created reservoirs and traps that result from both structure and stratigraphic complexity.

Westward extension by continental margin collapse of the Alboran Sea microplate in the Early Neogene has initiated large slump-block movements along the Iberic and Moroccan continental margins. Extensive allochthonous Late Cretaceous-Paleogene salt, deposited in a paleobasin having a western limit of 10°W to 12°W may underlie the slump-blocks at depths from 20 to 25 km and temperatures from 450° to 600°C, assuming 25°C/km gradient, and could serve as a lubricant for gravity-driven translation. Overall movement may exceed 400 km. The migrating blocks, operating as thin-skinned tectonics, and associated down-dip debris flows may be trapping mechanisms for hydrocarbons. Migrating debris covers an area as great as 90,000 km2, an area approximately equivalent to that covered by salt in the Gulf of Mexico.

The eastern terminus of the Azores triple junction is well marked by shallow earthquakes (<45 km and many <30 km deep). The junction passes beneath the Gulf of Cadiz and its continental margin. Major igneous extrusions, resulting in seamount growth especially during the upper Neogene, characterize much of the bathymetrically complex Azores-Gibraltar deformation zone. The prograding Iberic and Moroccan continental rise and slope bury the tectonically active and potentially warm oceanic crust. In summary, tectonics as denoted by earthquakes within the crust (oceanic, transitional, and continental) indicates that heat is being generated and is migrating upward. Hot, upthrust basement blocks and normal sedimentary compaction thus may warm the petroleum system, and heat is transported

along the salt wedges/layers and diapirs; salt is from two to three times as heat conductive as sandy clay sediment. In their often-interrupted upward migration, hydrocarbons may be stored beneath the thrusted crustal blocks.

The specifics of this crustal tectonics have not been deciphered; deeper seismic penetration is needed. The possibility that the Gulf of Cadiz could contain abundant hydrocarbons is discussed. The potential oil and gas reserves may rival the size of those in the subsalt play if source rocks, maturation processes, migration routes, and reservoir systems are found to occur. At present, some 180,000 to 360,000 km3 of sediments 2 to 4 km thick in the Gulf of Cadiz have never been explored by drilling.

Complex Petroleum Systems Developed by Subduction Process, Offshore Talara Basin, Northwest Peru

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Abstract

Study of 2-D marine seismic data of 1993 vintage along the Peruvian coast has led to the idea that subduction of marine sediments beneath a continental plate may be a potentially important mechanism for petroleum generation. The concept can be embodied in a new geologic model involving five essential factors:

1. Subduction of both continental and oceanic sediments along the Peru Trench.
2. Incorporation into the subducted material of rich organic material from two different sources:
3. From the west: subducted deep-ocean sediments.
4. From above: organic matter precipitated from the surficial Humboldt Current.
5. Probable duration of this previously unexamined mechanism during the past 100 million years.
6. Upward migration of the thermally mature, buoyant hydrocarbon fluids (first as liquid petroleum, later as natural gas) through the shattered sediments and along normal faults cutting the slope margin.
7. Entrapment of rising hydrocarbons in anticlinal closures, normal fault-blocks and fluviodeltaic stratigraphic traps.

Hydrocarbon formation must have benefited from unique oceanographic-geologic conditions associated with the "El Niño" phenomenon, and probably effective for the past 20-25 Ma. El Niño periodically generates a massive erosion of the coastal plain, which provides reservoir-grade sediments to the continental slope. Normal organic output from the nutrient-rich Humboldt Current is a primary factor in the creation of source rocks; the other source is subducted deep-sea sediments. Shallow cores taken during Leg 112 of DSDP (Yeats *et al,* 1976) indicate total organic carbon (TOC) ranging from 0.5% to 2.0%. Hydrocarbon generation could take place after incorporation into the subduction zone. Subsidence and burial of Tertiary, Mesozoic, and Paleozoic sediments would also provide hydrocarbon sources, whether derived from the paleo-shelf or the paleo-slope. The presence of two separate hydrocarbon-generating systems would enhance the prospectiveness of the Peruvian continental margin. The logical place to commence exploration is westward from the prolific and long-developed onshore and shallow offshore sectors of the Talara Basin.