1

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Dynamic Interplay among Tectonics, Sedimentation, and Petroleum Systems: An Introduction and Overview

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ABSTRACT

In the past few decades, the petroleum industry has seen great exploration successes in petroliferous sedimentary basins worldwide; however, the net volume of hydrocarbons discovered each year has been declining since the late 1970s, and the number of new field discoveries per year has dropped since the early 1990s. We are finding hydrocarbons in more difficult places and in more subtle traps. Although geophysical and engineering technologies are crucial to much of the exploration success, fundamentally, the success is dependent on innovative play concepts associated with spatial and temporal relationships among deformation, deposition, and hydrocarbon accumulation.

Unraveling the dynamic interplay among tectonics, sedimentation, and petroleum systems in the subsurface is a challenge and relies on an integrated approach that combines seismic imaging, well logging, physical and/or computational modeling, as well as outcrop analogs. In recent decades, an increasing coverage of high-quality three-dimensional (3-D) seismic data, along with state-of-the-art 3-D visualization technologies, extensive well tests, sophisticated modeling capabilities, and field (outcrop) analogs, has significantly added to our understanding of subsurface complexities in structure, stratigraphy, and petroleum systems. This volume is intended to provide a snapshot of the most recent advances in petroleum exploration by presenting state-of-the-art reviews and overviews, current case studies, and the latest modeling results. The reviews and overviews offer the current status of knowledge in extensional, strike-slip, and contractional tectonic settings, as well as their influence on sedimentation and hydrocarbon accumulation. The case studies cover diverse geologic settings, with special reference to the most prolific high-profile frontier sedimentary basins, such as those in west Africa, east Africa, east Brazil, Gulf of Mexico, South China Sea, Russian Arctic, and the Mediterranean Sea. The models provide both numerical and physical simulations of basin structures as well as their spatial variation and temporal evolution in response to different tectonic processes. The objective of this volume is to contribute toward an enhanced understanding of the spatial and temporal relationships among tectonics of different structural styles, syntectonic sedimentation, and hydrocarbon accumulation. Achieving this objective is the key to

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overcoming the challenges that we face in the exploration for hydrocarbons in complex reservoirs, subtle traps, and in increasingly difficult places at a time of growing global demand for energy.

REVIEWS, CASE STUDIES, AND MODELS

In Chapter 2, Davison and Underhill (2012) provide a review of extensional tectonics and its control on sedimentation patterns and hydrocarbon generation and accumulation. In an extensional tectonic setting, extremely prolific source rocks may be produced during the rapid rifting phase, particularly if half-graben depocenters are starved and oceanographic circulation is poor. The authors cite several recent studies demonstrating that thick (unfaulted) sag basins can develop very rapidly above rifted continental crust. In these circumstances, subsidence is thought to be too rapid to have been produced by normal thermal conductive cooling and is believed to have been produced by stretching of the lower or middle crust with no observable faulting. In particular, the authors report several important observations and findings. First, hotter, highly extended shallow basins generally contain fewer hydrocarbon fields than colder rift basins because the fault spacing in these shallower basins is relatively small and also because heat maintains the rift elevation so that deep lakes (source rocks) are generally not developed. Second, a simple shear rift basin may have a rift geometry and sedimentary fill that are similar to those of an asymmetric half graben produced by pure shear, but the simple shear case will have a lesser thermal subsidence sag phase developed directly above the central rift axis. Third, the initial dip of faults can be critical because high-angle faults produce faster subsidence rates than low-angle faults for a given strain rate, thereby favoring deep rift lake development. Fourth, the largest faults will form the deepest adjacent hanging-wall half graben, and these will be the preferred sites of lake development in continental rifts. Finally, transfer faults are a preferred location for clastic sediments to enter the rift, for complex structural closures, and for natural convergent points for hydrocarbon accumulation. Consequently, they are commonly a focus for hydrocarbon prospecting.

In Chapter 3, Mann (2012) compiles and describes structural styles in four active strike-slip regions with known concentrations of giant oil and gas fields including the following strike-slip fault system: (1) the Californian San Andreas; (2) the southern Caribbean Bocono–El Pilar; (3) the Sumatra; and (4) the eastern China. In each of the four study areas, the author compiles the main geologic and tectonic parameters that include (1) regional plate motions; (2) basin types along the strike-slip faults; (3) structural styles along strike-slip faults; and (4) structural and stratigraphic traps that accommodate large accumulations of hydrocarbons.

Based on the compilation and comparison, the author states that despite the relative paucity of giant fields found associated with strike-slip faults, several active strike-slip basins have produced billions of barrels of oil and deserve special analysis to understand the regional controls on their past productivity and reserve estimates. Furthermore, the author reports the following important observations and interpretations. (1) Regional compressive stresses are commonly oriented at right angles to strike-slip faults, indicating that these faults are surfaces of low shear stress. (2) Folds are parallel to the strike-slip fault (instead of oblique or en echelon). This supports the idea of strike-slip fault normal shortening instead of the more classical view of maximum compressive stresses that are obliquely inclined to the strike-slip fault plane and controlling the generation of en echelon arrays of folds and normal faults. (3) En echelon folds and faults are present in some settings where regional compressive stresses are oblique to fault trends, but en echelon folds and faults are less prevalent than fault-normal folds and faults based on this compilation. (4) Large strike-slip faults, with their parallelism to continental margins and regional compressive stresses at high angles to continental margins, may be closely controlled by active oblique subduction of oceanic plates occurring along offshore trenches at varying distances to the strike-slip areas. (5) The hydrocarbon potential of active strike-slip areas are handicapped by seal failures related to continued activity on strike-slip faults; however, despite this problem, many transpressive basins are removed from the locus of activity along major strike-slip faults and form well-sealed environments for hydrocarbon accumulations.

In Chapter 4, Ettensohn and Lierman (2012) provide a review and discussion of tectonic controls on the origin of Paleozoic dark shale basins in the Appalachian foreland, eastern United States. Recent mapping of dark shale units in the Appalachian Basin has shown that these units are major parts of unconformity-bound sequences that form during episodes of rapid loading-related subsidence and subsequent relaxation in the foreland basin. These episodes of subsidence and relaxation are related to coeval phases of tectonism that were mediated by collisions with successive continental promontories during orogeny. Early parts of the sequences include a basal unconformity and an overlying succession of dark shale that represents accumulation of organic-rich mud at a time when clastic sources were not yet developed and when sedimentation could not keep pace with subsidence. Once active loading and deformation ceased, the lithosphere responded by relaxing in a series of steps that allowed the basin to infill progressively with flyschlike and molasselike clastic sediments. As a result, 13 such cycles were generated during the Taconian, Salinic, Acadian/Neoacadian, and Alleghanian orogenies in the Appalachian Basin. Each cycle contains a major dark shale unit and an overlying coarser clastic sequence. Every part of the cycle has potential economic importance. Dark shale units become major hydrocarbon source rocks, and many of the overlying coarser clastic units develop into reservoir rocks.

The authors also recognize the diachronous nature of tectonic loading and basin formation along the Appalachian foreland. In a simple and typical case, if the collision and transfer were synchronous along the entire continental margin, the basin and forebulge would migrate perpendicular to the strike of the orogen. However, in an oblique collisional situation, the convergence becomes diachronous along strike, and basin forebulge migration exhibits a major component parallel to strike. Consequently, lithologies in each cycle also migrated in space and time, tracking the progress of convergence along the margin.

In Chapter 5, Gomes et al. (2012) provide a description of the intrabasinal Out High of the Santos Basin that formed during an early phase of rifting and thermal subsidence (sag). The extreme extension of the continental crust in this situation led to deep crustal, and even upper mantle, exhumation along with northwest-trending transfer on a fault system that runs between and separates the extensional segments. The extensional (rift) structures were later affected by postrift strike-slip structures, which were associated with continental breakup and opening of the South Atlantic Ocean. The presalt section of the deep-water Santos Basin forms a unique and attractive exploration play that features prolific and mature source rocks, synrift structural highs as four-way closures, a regional focus for hydrocarbon migration, and an overlying evaporite seal. The upper evaporite seal is thick and continuous, which contrasts with the inboard part of the Santos and Campos basins, where salt windows provided migration avenues from presalt sources to postsalt reservoirs. However, uncertainties exist about the association between reservoir presence and deliverability, and a long and heated debate has developed about the viability of siliciclastic reservoir models versus carbonate reservoir models (with enhanced reservoir quality from karstic carbonate facies) for the presalt section.

In Chapter 6, Lopez-Gamundi and Barragan (2012) present a case study showcasing the seismic expression of extensional structures of presalt, Early Cretaceous half grabens, and synrift and postrift sag sequences in the Greater Campos Basin at the southeastern continental margin of offshore Brazil. Based on recently acquired high-quality, prestack, depth-migrated seismic data, they provide evidence for distinct reflection characters and geometries of sequences formed in response to the faulting and rotation of half grabens that preceded thermal subsidence. They interpret that thickening and/or fanning (divergence) onto the fault margins and thinning and/or onlap (convergence) onto the flexural margins of the half grabens are indicative of differential subsidence caused by an early rift phase with an episode of rotation of fault blocks bound by planar faults (domino style). Moreover, the asymmetric geometry defined by the fault and flexure margins is shown to have affected across-axis variations in thickness and depositional facies of source and reservoir rocks in the synrift and postrift sag sequences. From a fault margin that features thickening and compaction to a flexural margin that features thinning and onlapping, the seismic boundary between synrift and postrift sag sequences becomes progressively angular and recognizable. The seismic base of the sag commonly shows a pronounced impedance contrast characterized by a clear and continuous reflection event. This event also shows lateral changes in amplitude character, probably reflecting changes in lithology from margins dominated by shallow-water conditions to deep basin centers. In the deep basin centers, similar lithologies are more likely to occur above and below the base of the sag, thereby inducing a rather subdued impedance contrast.

According to the authors, structural asymmetry caused by differential subsidence created optimal conditions for the deposition of lacustrine-to-brackish source rocks in the hanging-wall area of maximum accommodation space next to the fault margins of half grabens. The fault margin itself, however, is characterized by a low potential for high-quality clastic reservoirs because of underfilled conditions and provenance. The flexural margin of a half graben is a site of low subsidence and little accommodation space suitable for the development of high-energy carbonates. In contrast, a distinctive sag-facies association commonly forms on bathymetric highs developed on underlying rift shoulders. This facies association contains microbial limestone deposited in subtidal-to-peritidal environments.

In addition, the authors discuss the structural and stratigraphic traps associated with rifting and postrift subsidence. Differential compaction at a fault margin is a key factor in creating the counterregional dip necessary to form structural four-way closures at the sag level. Combined structural-stratigraphic traps are defined by an updip pinch-out component at the base of the sag or at any horizon within the sag interval. Updip onlap and three-way closures define these combined traps. Potential for onlap and/or pinch-out traps is also present at the rift-fill level on the flexural flank of half grabens. Along the rift axis, the polarity of half grabens switch vergence across intervening accommodation zones (transfer faults) in a pattern similar to that observed in the East African rifts. This kind of architecture can contain four-way closures that provide optimal conditions for focused hydrocarbon accumulation.

In Chapter 7, Oliveira et al. (2012) present a discussion about basin slope contractional tectonics linked to upslope extensional tectonics in shale-dominated gravitational gliding systems in the Pará-Maranhão and Barreirinhas basins of Brazil. Both basins lack salt detachments, which contrast strongly with other basins on the passive continental margins of the South Atlantic Ocean. As opposed to salt-based systems, the gravitational systems reported in this chapter detach on a decollement surface of presumably overpressured shale and marl at depths of about 6 km (~3.37 mi). The known exploration successes in the contractional domains of shale-detached gravitational systems in the distal parts of deltas in Nigeria, Indonesia, Trinidad and Tobago, Egypt, India, and Brunei hold the promise of high potential at the equatorial margins of Brazil and Africa where shale-based gravitational systems are also present.

By integrating seismic interpretation, physical and/or numerical modeling, structural restoration, and field investigation, the authors demonstrate that thrusts developed in a backstepping sequence such that depocenters migrated landward through time. Their results show that the total amount of shortening exceeded the total amount of stretching in basal layers close to the detachment surface, whereas stretching exceeded shortening in the upper layers. Among the possible reasons for the excess of total shortening over total stretching in the basal layers is evidence for a greater amount of compression over shale detachments than over salt detachments. Furthermore, physical modeling that best reproduced the structural features similar to those present in the Barreirinhas Basin was the one that simulated two bordering dextral strike-slip faults, analogous to the Romanche and Saint Paul fracture zones that bounded the gravitational cell. Resulting high pore pressures in the shales and marls, which might have induced the gliding, possibly originated from hydrocarbon generation. Understanding similar spatial and temporal relationships could be instrumental in unraveling the dynamic interplay among deep-water basin slope thrusting, strike-slip tectonics, sedimentation, and fluid flow.

In Chapter 8, Tiercelin et al. (2012) report on the Mesozoic and Early–Middle Cenozoic rift basins of central and northern Kenya (East African rift) and their relationships to hydrocarbon prospects. In terms of source rock quality and reservoir properties, they review the evidence of oil potential in a suite of Cretaceous(?)–Paleogene and Paleogene–Middle Miocene basins identified in the two regions. The study provides an important set of data for potential oil exploration in these rift basins. In addition to the variation in structural styles through time, hydrocarbon potential seems to be mostly controlled by the nature of the basin-fill stratigraphy. Sedimentologic, petrologic, and geochemical studies conducted on likely reservoir and source rocks in the major basins permit the development of a provisional ranking of these basins in terms of source rock quality and quantity, reservoir potential, and hydrocarbon prospects. These can be very important in future exploration and well-bore planning in the rift basins.

In Chapter 9, Abeinomugisha et al. (2012) describe the Tertiary Albertine Graben, a part of the East African rift system, as a classic example of the processes of continental breakup. The graben has experienced several extensional and transpressional episodes, resulting in structures that are typical to both settings. They describe variations in graben geometry, sedimentation, and prospect potential along the graben segmented by intersecting accommodation zones. All the wells drilled in the graben have been on either positive flower (palm tree) structures or on rotated fault blocks. Despite the excellent hydrocarbon potential of the graben, several issues remain poorly resolved, including source rock depositional environments, migration pathways, and trapping mechanisms. A geologic section along the strike of the graben indicates two subbasins separated by an accommodation zone. The authors conclude that the Albertine Graben evolved through multiple phases of tectonic deformation, involving both extension and inversion (compression). Extensional regimes created accommodation space for the accumulation of a thick sequence of sediments necessary for the generation of hydrocarbons. However, early extensional and subsequent contractional regimes created both effective hydrocarbon migration pathways and structural traps. All the discoveries made to date are structurally controlled and are mainly in contractional anticlines developed along basin margin faults. The high potential of the petroleum system is spatially associated with transfer faults that controlled the along-axis variation in graben geometry and sedimentation.

In Chapter 10, Gao and Milliken (2012) use high-quality 3-D seismic data to discuss basin-scale lineaments in the Lower Congo Basin at the west African passive continental margin. Among the different structural grains, they focus on cross-regional intraslope lineaments and their implications for hydrocarbon accumulation in the postsalt Tertiary section. These lineaments are spatially associated with allochthonous salt bodies, turbidite channel systems, hydrocarbon field discoveries, and direct hydrocarbon indicators. Seismic evidence suggests that the cross-regional lineaments might have had a significant strike-slip component and that they are spatially associated with, but kinematically different from, regional thrusts and folds. Moreover, the authors suggest that these lineaments are transfer faults (tear faults) induced by regional gravitational sliding involving the postsalt sedimentary section. The authors further speculate that the northeast-trending lineaments could be an expression of presalt basement-involved transfer faults associated with the Early Cretaceous rifting of the continent. The obliquity of the northeast-trending (45°) continental transfer faults relative to the northeast–east-trending (80°) oceanic fracture zones of the South Atlantic can be explained by a finite 35° counterclockwise rotation of the west African continental margin. This obliquity is strikingly similar to (but with an opposite polarity) that reported at the Campos Basin along the eastern Brazilian continental margin, which indicates an opposite clockwise rotation of the east Brazilian continental margin. Such relationships and patterns from both conjugate continental margins may well be seismic evidence of the southward scissorslike opening of the South Atlantic Ocean, which in turn sheds new light on the diachronous nature and timing of the sedimentary basins along the west African passive continental margin.

Numerous major oil and gas field discoveries that apparently reflect focused commercial hydrocarbon accumulation along the lineaments underscore the economic implications of these lineaments. In the authors' discussion regarding the implications of cross-regional lineaments in the Lower Congo Basin and in other petroliferous sedimentary basins worldwide, they argue that high-angle dip and intensive shear deformation along the lineaments were favorable for effective hydrocarbon migration from the deep source to the shallow reservoirs. They additionally suggest that these cross-regional lineaments have significant strike-slip components, and that strike-slip faults could have had a different, if not more important, function in the accumulation of hydrocarbons than low-angle dip-slip faults. Such a function is particularly important in parts of basin slopes where extensive toe thrusts and folds associated with salt provide effective traps, and structural migration pathways become critical for hydrocarbon migration from deeply buried sources to shallower reservoirs. Given the uncertainty of vertical relationships between presalt basement transfer faults and the cross-regional lineaments shown in the postsalt Tertiary seismic section, the authors have stressed the importance of differentiating postsalt lineaments (detachment structures) from the presalt, deeply rooted, transfer faults (basement structures). Hence, better seismic imaging and a more complete understanding of the vertical extent of these cross-regional lineaments could be instrumental in evaluating the hydrocarbon potential of presalt and postsalt petroleum systems and the connectivity of the presalt source rock in the rift sequence to the postsalt Tertiary reservoirs of the passive-margin sequence.

In Chapter 11, Linzer and Tari (2012), for the first time, make lithologic and structural correlations between the classic Alpine folded belt of the Northern Calcareous Alps (NCA) of Austria and the Transdanubian Central Range (TCR) of Hungary, which presently is located some 200 km (~12.4 mi) away. It is widely accepted that the NCA of Austria and Germany represents a thin-skinned, fold-and-thrust belt along the northern margin of the Eastern Alps, whereas the TCR of Hungary is traditionally considered to be a simple autochthonous unit without any internal deformation. The allochthonous versus autochthonous nature of the TCR is still a subject of debate. Nonetheless, palinspastic restoration of the post-nappe deformation presented in this Chapter clearly reveals the spatial and temporal relationship between these major Alpine units despite their present-day separation and indicates clockwise rotation of the NCA and counterclockwise rotation of the TCR.

The TCR has seen several hydrocarbon exploration campaigns on its northwestern flank, but the NCA remains practically unexplored. Seismic sections illustrate the same overall Alpine characteristics in both the NCA and the TCR. The internal structures of the NCA are highlighted by a set of dextral strike-slip faults interpreted as tear faults or transfer faults caused by right-lateral oblique convergence. The strike-slip faults terminate at depth at the same detachment as that of the internal thrusts. In the clastic basins of the western NCA, deep-water sediments were separated from shallow-water sediments by these transfer faults, attesting to their syndeformational nature. In comparison with the NCA, the Eo-Alpine thrust systems of the

TCR are not as well known. However, seismic reflection data indicate that the TCR was, just as the NCA, dismembered by west–northwest-oriented dextral strike-slip faults during the Cretaceous. The TCR structural pattern of northeast-trending thrust boundaries and fold axes and the northwest orientation of the dextral strike-slip faults appear to be identical with those of the NCA in terms of geometry and timing. Hence, the similarity in structural patterns suggests a coherently deformed Eo-Alpine nappe stack along with a cross-strike, strike-slip (transfer or tear) fault. The recognition of a once continuous, regional, right-lateral strike-slip fault system in the NCA/TCR areas has important implications for pre-Tertiary kinematic reconstructions of the broader Eastern Alps and Pannonian Basin region. This reconstruction could lead to a better understanding of the regional tectonic architecture, growth history, and control on syntectonic deposition. Understanding these aspects is fundamental to future hydrocarbon exploration in this mostly unexplored region.

In Chapter 12, Verzhbitsky et al. (2012) use newly acquired and processed two-dimensional (2-D) seismic data and field geologic observations to discuss the tectonics and hydrocarbon potential of the South Chukchi Basin (Chukchi Sea, Russian Arctic). Their analysis of onshore data points to the beginning of sedimentation during the Aptian–Late Cretaceous. The geometry of the faults indicates an extensional and/or transtensional setting, although folds, thrust faults, pop-up and positive flower structures also occur, indicating local development of compressional and transpressional structural styles. The South Chukchi Basin experienced multiphase extension and/or right-lateral transtension and subsidence during the Paleocene–Quaternary. The existence of a prerift thrust system at the base of the basin suggests that the South Chukchi Basin inherited a preexisting Late Mesozoic zone of displacement and that the basin was formed during the Aptian–Late Cretaceous–Cenozoic as a result of the change in tectonic setting from compression in the Neocomian to subsequent extension. The observed right-lateral component of the youngest south-dipping normal faults and transtensional structures identified on seismic sections also indicate the function of dextral strike-slip movements in the development of the South Chukchi Basin. Structural and stratigraphic traps associated with bright spot anomalies and gas chimneys suggest that hydrocarbon potential in the South Chukchi Basin may be significantly higher than previously recognized. An investigation of the spatial and temporal relationships among strike-slip, extensional, and contractional structural styles based on seismic and outcrop observations will have important implications for future hydrocarbon exploration in this frontier Arctic sedimentary basin.

In Chapter 13, Anderson et al. (2012) examine the Oligocene–Miocene evolution of the Lower Congo Basin and how variations in structural style and history along the strike of the basin affected the distribution of reservoir sandstones on a regional scale. The authors provide examples of the interaction between active structures and syntectonic sediments, showing that evolving structures exerted a primary control on distribution and architecture of deep-water reservoirs. The Oligocene–Miocene paleogeographic evolution of the Lower Congo Basin demonstrates the interaction of active structures with deep-water depositional systems as a progradational passive margin evolved through time. Slope gradient generally became steeper through time as progradation of the shelf edge advanced and generated systematic changes in large-scale reservoir geometry, distribution, and organization. In addition, overprinting this large-scale slope gradient change were local changes in sea-floor gradient caused by active gravitational structures. This local gradient perturbation apparently resulted in rapid lateral changes in accommodation space affecting the deposition of reservoir facies. The study shows that interaction between active structures and reservoirs may be subtle and episodic and may be better detected by observing channel trends and behaviors near active faults and folds in map view instead of by relying entirely on cross sectional stratal geometries such as onlap or truncation.

In Chapter 14, Clark and Cartwright (2012) consider how the relative rates of sedimentation and uplift vary along the strike of folds in the Levant Basin of the eastern Mediterranean Sea, where deep-marine growth structures and channel-levee systems are key targets for hydrocarbon exploration. In particular, the authors provide detailed documentation on the interplay among folding, strike-slip faulting, and sedimentation in deep-water channel-levee systems. They demonstrate spatial and temporal relationships between thrust-related folding and strike-slip faulting at the fold terminations and show that multiple submarine channel-levee systems were coeval with structural development. Based on the variation in onlap observed along the strike of the fold, a zone of increased structural relief is located adjacent to the segment boundaries (lateral terminations) of strike-slip faults, which could represent the earliest onset of folding. In addition, uplift maxima are located toward the lateral terminations of folds with strike-slip faults, resulting in increased stratal thinning along those strike-slip faults where the lateral terminations act as sediment barriers. This situation contrasts with systems in which the maximum fold amplitude is located in the center and decreases toward the lateral tip regions. In addition, the authors discuss factors that affect the architecture of growth folds and their along-strike variations, emphasizing possible problems that may result from interpretations based solely on limited outcrops or 2-D seismic lines. The influence of such structures in a submarine lower fan setting is especially telling. In this setting, channel axes are mostly confined by the levees and not by incision, and increased channel aggradation may allow a channel flowing perpendicular to folds to maintain its course, particularly if the uplift rate is low relative to sedimentation rate. However, if the uplift rate is relatively high, as indicated by an increasing occurrence of onlap on the limbs of anticlines, a channel becomes blocked or diverted, indicating coeval structural uplift and sedimentation.

In Chapter 15, Tari et al. (2012) report on three deep-water exploration wells from the underexplored Moroccan salt basin in the deep water of West African Atlantic. The basin features a contractional toe thrust and fold belt and a mid-Tertiary allochthonous salt that was sourced from the latest Triassic to earliest Jurassic autochthonous salt level that was deposited during synrift margin evolution. The central part of the Moroccan Atlantic margin is adjacent to the Atlas Mountains. One would expect a much larger sedimentary influx and, therefore, more clastic reservoir facies in this segment of the African margin than, for example, farther to the south. Yet, the three deep-water exploration wells were all dry holes and basically documented the same general lack of clastic reservoirs that is observed throughout the entire Tertiary–Upper Cretaceous succession.

The authors present different scenarios for explaining the apparent lack of reservoirs in the deep-water domain of central Atlantic Morocco. First, the well locations could be inboard of the paleochannel lobe–transition zone and therefore the reservoirs might be expected farther out. Second, the wells could have been drilled outboard of reservoir facies that were trapped closer to the paleoshelf edge. Third, the well locations could have been in a paleosediment shadow zone, bypassed by potential reservoir facies. The authors also discuss and predict the existence of potential reservoir facies equivalent to other siliciclastic turbidites based on regional correlation, outcrop, and the presence of a shallow-water to onshore deltaic complex. They also suggest the presence of Jurassic reservoirs based on high-amplitude fanlike geometries identified in seismic reflection data. However, these possible reservoirs occur seaward of the toe thrust belt and appear to be relatively small and thin.

In Chapter 16, Londono et al. (2012) present a study based on modeling of lithospheric flexure and related base-level stratigraphic cycles in the Putumayo Foreland Basin, Northern Andes, showing that the basin history is different from the current evolutionary concept proposed for the basin. Their results suggest that onlapping seismic facies migrated toward the foreland predominantly during sediment-controlled flexural periods, whereas onlapping seismic facies migrated toward the hinterland when thrusts belt loads dominated. On average, tectonic-loading subsidence is thought to be responsible for about 23% of the total subsidence, whereas sediment loading is responsible for the remaining 77%. Moreover, the sandstone/shale ratio is interpreted to increase with an increasing ratio of sediment-related subsidence to tectonic-related subsidence.

According to the authors, the geometry of the effective thrust belt and the wavelength of the lithospheric deflection preclude the need to invoke dynamic topography as a downward force acting on the plate to create extra accommodation in the basin. As is manifest in their results, the geometry of the loads apparently had a strong control on the final geometry of the basin. Tectonic loads produced forebulges that were closer to the hinterland and deflections that were narrower and deeper than those created by sedimentary loads. According to the subsidence regime, the authors divide the sedimentary sequence into two facies. The first is a tectonically induced high-subsidence facies, with probably low sandstone/shale ratios, that is predicted to have been associated with onlap shifts toward the hinterland. The second is a sediment loading-induced low-subsidence facies, with probably high sandstone/shale ratios, that is predicted to have been associated with continual onlap events toward the foreland bounded by onlap shifts and/or unconformities. The authors also suggest that tectonic events produced a narrow but deep depocenter with a high subsidence rate (in relation to sediment supply) and a low sandstone/shale ratio. In the seismostratigraphic record, a tectonic-loading event would be recognized by regional (tens of kilometers) onlap shifts from the foreland toward the hinterland. Conversely, a sediment-related subsidence event (controlled mostly by the weight and dispersion of sediments) would produce a wide but relatively shallow depocenter with high sedimentation rates compared with subsidence rates and a high sandstone/shale ratio. During these sediment-related events, flexure should be expected to widen as sediments propagate toward the foreland. Discoveries of commercial heavy oil in an adjacent foreland basin could indicate that the Putumayo foreland has hydrocarbon potential, especially with traps developed in or around forebulges coeval with each loading event.

In Chapter 17, Luo and Nummedal (2012) show the results of 3-D flexural numerical modeling and a subsurface study in southwestern Wyoming to identify Late Cretaceous forebulge location and migration in response to thrust loads. They recognize three forebulges with respective amplitudes ranging from 40 to 70 m (120–210 ft) and widths ranging from 30 to 50 km (~20–30 mi). Their data indicate that the forebulges migrated eastward (basinward) in spatial and temporal association with progressively younger thrusting in the Wyoming thrust belt. The width of the foredeep (the distance from the thrust front to the associated forebulge) was between 160 and 194 km (~100–121 mi). They performed 3-D flexural numerical modeling using an elastic lithospheric model, which was achieved by solving a differential equation for the vertical deflection of a thin elastic plate over a fluid substratum with a specific applied surface load. Their modeling results are reportedly consistent with the geologic observations of forebulge migration and explain the complexity of the 3-D distribution of forebulge-related unconformities in the subsurface of the Greater Green River Basin.

In Chapter 18, Yang et al. (2012) provide an overview of different generations of the South China Sea (SCS) polyhistory basins and discuss their implications for hydrocarbon exploration. On the basis of previous studies and most recent advances in polyhistory basin classification schemes, they divide the evolution of the SCS Basin into two cycles: an early divergent-convergent cycle and a later divergent-convergent cycle. Geohistory analysis suggests that the SCS Basin has experienced multiphase deformation, creating an assemblage of numerous basins of different generations and styles.

The authors emphasize the physical condition of each basin and the overprinting (temporal) relationships of different basins. Each basin features a specific pressure, space, and temperature at a specific geologic time in the basin history, whereas overprinting of a different basin could cause changes in pressure, space and temperature with time, leading to changes (either enhancement or reduction) in the hydrocarbon potential of the basin. Therefore, the polyhistory basin analysis is helpful in evaluating hydrocarbon potential from a dynamic and historic perspective in the SCS.

STRUCTURAL STYLES IN PETROLEUM SYSTEMS

State-of-the-art reviews and/or overviews, current case studies, and recent numerical and/or physical modeling results presented in this *Memoir* demonstrate how different structural styles influence the effectiveness, thickness, and spatial distribution of source, reservoir, and seal/cap rocks, as well as migration pathways and traps in such a different manner as to enhance (or hinder) hydrocarbon generation and accumulation. Understanding the influence of different structural styles in petroleum systems can be crucial to exploration success by better predicting risk factors in more difficult basins.

Extensional structures and tectonics, particularly those at the crustal scale associated with rifting and thermal subsidence, have a major function in controlling basinwide syntectonic sedimentation in the development of petroleum systems (Brice et al., 1982; Harris et al., 2004; Guiraud et al., 2010; Versfelt, 2010; Davison and Underhill, 2012; Gomes et al., 2012; Lopez-Gamundi and Barragan, 2012; Tiercelin et al., 2012; Abeinomugisha et al., 2012). Crustal-scale extension could lead to significant thinning of the crust that is accommodated by regional grabens as well as by cross-regional strike-slip transfer faults (e.g., Wernicke, 1981; Bosworth, 1985; Barr, 1987; Talbot, 1988; Frostick and Reid, 1989; Jackson and White, 1989; Figueiredo et al., 1995; Katz, 1995; Lambiase and Bosworth, 1995; Morley, 1995; Gawthorpe and Leeder, 2000; Davison and Underhill, 2012). Major crustal extension is most effective at creating accommodation space, allowing for the influx and deposition of thick sequences of sediments that can later become prolific source, reservoir, and seal/cap rocks (Harris et al., 2004). For example, extreme stretching in highly extended terranes can lead to significant crustal thinning and denudation, causing major crustal isostatic rebound that could complicate the geothermal gradient and maturation history of intracontinental rift basins (Davison and Underhill, 2012; Abeinomugisha et al., 2012). This could be different from contractional foreland basins, where the impinging thrust front can cannibalize and disrupt any maturation that may have been occurring. This could also be different from strike-slip pull-apart basins, where focused sedimentation and limited isostatic rebound occur.

Strike-slip structures and tectonics play yet a different function in a working petroleum system and have contributed significantly to the accumulation of oil and gas (Mann et al., 2003; Mann, 2012). Strike-slip faults have three characteristics (Stone, 1969; Harding, 1973, 1990; Wilcox et al., 1973; Crowell, 1974; Fleming and Johnson, 1989; Xu, 1993) that make significant differences in controlling fluid-flow efficiency and direction. First, strike-slip faults are typically vertical or subvertical (Stone, 1969; Harding, 1973). Vertical or subvertical faults can be most straightforward migration pathways for fluid to flow efficiently from source to reservoirs. Second, strike-slip faults are typically characterized by a large lateral component of slip, producing highly strained and/or intensively fractured fault zones with enhanced fracture connectivity, porosity, and permeability. These can be important attributes controlling the efficiency and extent that fluids can flow. Third, steeply dipping strike-slip faults are oriented in such a way that the effects of gravity (overburden) on hydraulic properties along the faults are relatively insignificant compared with shallowly dipping thrusts or normal faults; whereas the effect of tectonic stress on hydraulic properties along the faults depends on the partitioning between extensional and/or contractional stress and shear stress (Wilcox et al., 1973; Mann, 2012). Such a stress state and high pressure gradient associated with vertical strike-slip faults could make the faults effective fluid pumps. However, continued deformation along active strike-slip faults may jeopardize the retention of trapped hydrocarbons because of the enhanced likelihood of fluid leakage along the faults. In addition, although strike-slip faults can also control the play fairways and create thick sequences of syntectonic deposits, the deposits are relatively focused, localized, and linearly distributed as in the pull-apart basins (Crowell, 1974; Mann et al., 2003) compared with those in extensional tectonics settings (Lambiase and Bosworth, 1995; Morley, 1995; Gawthorpe and Leeder, 2000; Harris et al., 2004) or contractional foreland basins (Ettensohn and Lierman, 2012; Londono et al., 2012; Luo and Nummedal, 2012).

Contractional structures and tectonics are yet another structural style that has had an important and different function in petroleum systems. Unlike extensional and strike-slip tectonics, crustal contraction generally creates regional distributed folds and thrusts that are commonly associated with overpressured salt and/or shale (Fox, 1959; Dahlstrom, 1970; Harris and Milici, 1977; Suppe, 1980; Gries, 1983; Mitra, 1988; Suppe et al., 1992; Weimer and Buffler, 1992; Shaw and Suppe, 1994; Rowan, 1997). These can make contractional structures effective traps and seals for oil and gas, although traps can also be found in extensional and strike-slip structures (Davison and Underhill, 2012; Mann, 2012; Verzhbitsky et al., 2012). Tectonic loading of the crust by large-scale folding and thrusting creates foreland basins in which basinwide deposition can create source and reservoir rocks (Ettensohn, 1994; Ettensohn and Lierman, 2012). The lateral distribution and vertical stacking patterns of lithofacies and their thickness are spatially and temporally associated with the flexural forebulge that migrates in response to tectonic and/or sediment loading (Ettensohn, 1994; Ettensohn and Lierman, 2012; Londono et al., 2012; Luo and Nummedal, 2012). Although contractional faults can contribute to the syntectonic deposition of source, reservoir, and seal/cap rocks on a general basis, their lateral and/or vertical distribution pattern is significantly different from those in the extensional and strike-slip settings because of their distinct deformational, depositional, and geothermal settings.

INTERACTION OF STRUCTURAL STYLES IN PETROLEUM SYSTEMS

Results presented in this *Memoir* demonstrate that it is a combination or complementation of different components of a petroleum system that controls the potential of hydrocarbons. Because of such an integrated nature, any paucities or gaps in the system, which are critical exploration risk factors to the accumulation of oil and gas, directly define and thus point to the exploration direction or target. These could change from region to region depending on the dominant structural style of the region and from basin to basin depending on the tectonic regime of the basin.

In an extensional and/or passive-margin regime, many fields that appear to be in a seemingly simple setting turn out to have very complicated spatial and temporal relations to different structural styles and syntectonic sediments (Harding and Lowell, 1979; Mann et al., 2003; Davison and Underhill, 2012; Oliveira et al., 2012). For example, in the North Sea (Rouby et al., 1996), hydrocarbons commonly occur at the intersections of north–south-trending grabens with east–west-trending transfer faults. The steeply dipping transfer faults provide effective vertical migration pathways from deeply buried source rocks, associated with rifting and thermal subsidence (sag), to shallow structural and stratigraphic traps (Rouby et al., 1996). The transfer faults also influenced the location, direction, and distribution of channels or turbidites that are highly productive reservoirs (Rouby et al., 1996; Davison and Underhill, 2012). At the west African and eastern Brazilian passive continental margins above rift and sag basins, it is well known that the downslope deep-marine areas have prolific source rocks with extensive fetch area. It is also known that this region is dominated by gravity-induced thrusts, folds, and salt structures with a high sealing capacity. In addition, many recent deep-water drilling, 3-D seismic analyses, and outcrop studies (Kolla et al., 2001; Posamentier and Kolla, 2003; M. Gardner, 2005, personal communication) reveal great potential for reservoir presence in deep-marine turbidite systems. These studies lead to the conclusion that migration pathways could be a critical gap and, as such, strike-slip faults are of primary importance and have a crucial function in filling the gap because of their effectiveness as migration pathways. For example, in the Lower Congo Basin of offshore Angola (west Africa) (Cramez and Jackson, 2000; Da Costa et al., 2001;

Hudec and Jackson, 2002; Gawenda et al., 2004; Jackson et al., 2004; Nombo-Makaya and Han, 2009), cross-regional northeast-trending faults are spatially associated with many discoveries in the Tertiary sedimentary section (Gao and Milliken, 2012). Similarly, this spatial relationship occurs in the deep water of the Campos Basin, offshore Brazil, where extensive cross-regional northwest-trending lineaments cut across regional northeast-trending folds and thrusts in the Upper Cretaceous and Tertiary sections (Gao et al., 2009). Furthermore, as indicated by recent field discoveries, the relationship also occurs in the deep water of offshore equatorial Guinea (west Africa) (Lawrence et al., 2002) (e.g., the Alba Field, Lawrence et al., 2002; Wolak and Gardner, 2008), in deep water of offshore Gabon (west Africa) (e.g., the Tchitamba Field, Kilby et al., 2004), and in the deep-water Gulf of Mexico (U.S.A.) (Weimer and Buffler, 1992; Rowan, 1997). The spatial association of hydrocarbon fields with transfer faults is primarily caused by their high migration potential that is critical to the accumulation of oil and gas in the deep-water regions of passive margins. In contrast, the upslope shallow-marine areas of passive margins are dominated by gravity-induced extensional faults (Anderson et al., 2000; Oliveira et al., 2012) along with both siliclastic and carbonate reservoirs. Because extensional faults could enhance the migration potential, effective traps become the critical component in this part of the passive margin, and the exploration focus needs to change to finding traps such as rollover anticlines on the hanging wall of listric normal faults or cross-fault juxtaposition of shale or other rocks with a high sealing capacity. This concept could be used in building an exploration strategy and risk profile from the shelf down to the basin floor across passive continental margins.

In a wrench tectonic regime, strike-slip faults provide an optimal setting for fluid migration from source rocks to reservoirs. Examples include the many giant oil and gas fields along the northwest-trending San Andreas fault in the western United States (Harding, 1973, 1974; Crowell, 1974; Mann et al., 2003; Mann, 2012) and the major fields associated with the northeast-trending Tan-Lu fault in eastern China (Xu, 1993; Mann et al., 2003; Hsiao et al., 2004; Mann, 2012). Many strike-slip faults are commonly kinematically associated with either extensional (transfer faults) or contractional (tear faults) tectonics (Linzer and Tari, 2012; Mann, 2012). Actually, many oil and gas fields are directly associated with strike-slip faults, although they are located in extensional or contractional tectonic regimes. Examples include the hydrocarbon fields in the North Sea associated with the Mesozoic northeast-trending transfer faults across the grabens (Rouby et al., 1996), the Paleozoic northwest-trending lineaments across the rift in the Sirte Basin of Libya (Guiraud and Bosworth, 1997), the Paleozoic east–west-trending and northwest-trending lineaments across the Rome trough in the Appalachian Basin (Wheeler 1980; Shumaker, 1986; Gao and Shumaker 1996; Shumaker and Wilson, 1996; Gao et al., 2000), and the Paleozoic strike-slip faults in the Anadarko Basin and the Permian Basin (Mann et al., 2003). In a strike-slip tectonic regime, the exploration focuses should be directed at traps, together with source rocks and reservoirs. Typically, deposition of source and reservoir rocks occurs in a releasing bend (Crowell, 1974) or at the intersection with rift, and creation of traps occurs at the restraining bend (Crowell, 1974) or at the intersection with thrusts or folds. In eastern China, for example, Mesozoic and Cenozoic strike-slip faulting has had a major function in controlling the scale and distribution pattern of petroliferous sedimentary basins and major oil and gas fields. These include the most recent major oil fields found in the Bohai Bay Basin (Mann et al., 2003; Hsiao et al., 2004; Mann, 2012), a major pull-apart basin spatially and temporally associated with the strike-slip Tan-Lu fault (Mann, 2012). Along the San Andreas fault in the western United States, major oil and gas fields tend to cluster in the areas of major restraining bends at distances less than 100 km (<62 mi) from the San Andreas fault zone, where crustal shortening and thrust faulting in the vicinity of the restraining bend are associated with giant oil fields (Mann et al., 2003; Mann, 2012). In the Sirte Basin of Libya (Guiraud and Bosworth, 1997), major oil and gas fields are associated with regional northwest-trending strike-slip faults, particularly at their intersection with a northeast-trending rift that is filled with a thick sequence of source rocks and is overprinted by inversion structures that form structural traps.

In a contractional tectonic regime, many oil and gas fields have been found to be associated with the intersection of thrusts and folds with transfer and/or tear faults. For example, in the central Appalachian Basin in the eastern United States, a regional northeast-trending rift basin (Shumaker, 1986; Shumaker and Wilson, 1996) was segmented by cross-regional northwest-trending basement transfer faults during the Early Cambrian (Harris, 1978; Wheeler, 1980; Shumaker, 1986; Shumaker and Wilson, 1996; Gao et al., 2000). This early rift basin was overprinted by tectonic inversion, and the latter created extensive northeast-trending detachment folds and cross-strike lineaments that have been considered to be effective traps and migration pathways (Wheeler, 1980; Gao et al., 2000). In the foreland basin setting during the late Paleozoic, cyclic sedimentation that occurred in response to tectonic loading controlled the distribution of black shale as prolific source and reservoirs (Ettensohn, 1994; Ettensohn and

Lierman, 2012). Late Paleozoic thrust faults coupled with the northwest-trending cross-regional discontinuities or tear faults controlled syntectonic sedimentation and accumulation of oil and gas (Wheeler, 1980; Gao et al., 2000). Similar interaction also occurs in the Anadarko Basin, the Powder River Basin, the Fort Worth Basin, and the Permian Basin in the United States, in which many hydrocarbon fields are associated with the intersection of strike-slip faults with folds and thrusts (Gao, unpublished data). In the Fort Worth foreland basin, in particular, strike-slip faults are spatially associated with gas chimneys (Sullivan et al., 2006), a direct hydrocarbon indicator for natural gas, suggesting that these regional intrabasin strike-slip faults in a contractional foreland basin setting might represent high-potential sweet spots as exploration targets at their intersections with folds and thrusts.

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