face but also to be able to explain geologic concerns and solutions in terms understandable to engineers. Therefore, the geologic work in these fields is conducted at two levels. At the basic scientific level, interpretations of regional settings, depositional environments, facies distribution, and diagenetic and porosity trends are being carried out. At the applied level, this knowledge is integrated with engineering plans and modeling studies for projects such as delineation and infill drilling, well completions, waterflood, and enhanced oil recovery.

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Generation, Migration, and Entrapment of Hydrocarbons on Southern Norwegian Shelf

The Southern Norwegian Shelf (56°-58° 30'N) has proved to be one of the most prolific hydrocarbon provinces in Europe. Recoverable reserves of about 4.8 billion bbl of oil plus oil equivalent are found predominantly in Upper Cretaceous and Danian-age chalk and Jurassic sandstones. The excellent quality of seismic data, moderate to dense well control, and the detailed geochemical evaluations of the Kimmeridge Clay, the principal source rock, make the Southern Norwegian Shelf an ideal area for hydrocarbon generation studies.

A geochemical analysis of the area contained five basic steps: (1) construction of a nine-layered three-dimensional grid summarizing the burial history of the sediments by using well control and seismic data, (2) calculation of geothermal gradients, (3) source rock analysis to investigate variations in thickness and richness of the Kimmeridge Clay study area, (4) maturation study based on the results of the three initial steps, and (5) volumetric analysis and prospect evaluation.

Major factors affecting hydrocarbon accumulations in the structural and stratigraphic closures of the study area include the amount of oil generated within the catchment areas of the various closures and, particularly in the case of the chalk fields, the level of hydrocarbon generation of the Kimmeridge Clay directly under the crest of the structure and presence of faults to act as conduits for vertical migration of hydrocarbons from the Upper Jurassic Kimmeridge Clay to the Upper Cretaceous Danian chalk. The expulsion and migration efficiency (hydrocarbons in place/hydrocarbons generated within the catchment area of individual closures) for tested closures average approximately 8% for the study area, with individual culminations having values as high as 40% or as low as 0%, based in part on the previously mentioned factors.

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Carbonate Sequence Stratigraphy and Controls on Carbonate Platform Development—Case Study from Permian of West Texas-New Mexico

Integration of seismic stratigraphic concepts with detailed field studies and geohistory analysis provides powerful interpretation leverage for deciphering the complex geologic history of carbonate platform-basin areas. Changes in carbonate productivity as well as platform growth and the resultant facies distribution are controlled most importantly by changes in relative sea level.

The structural history of the Permian basin during the Permian shows two subsidence cycles of 10-20 m.y. duration. These subsidence cycles were major factors in the long-term (10^6 - 10^7 m.y.) development of the Permian carbonate platforms. During periods of relatively rapid subsidence, aggradation was dominant; during periods of slow subsidence, major platform progradation occurred.

Superimposed on the long-term tectonic cycles is a series of third-order eustatic cycles (0.5-3 m.y.), which controlled development of 27 depositional sequences. Each sequence is composed of three depositional systems tracts: (1) a lower basin-restricted wedge interpreted to have been deposited during a relative fall and lowstand of sea level, (2) a transgressive systems tract of variable thickness, and (3) an upper, relatively thick, aggradational-to-progradational carbonate platform system, which includes significant allochthonous deposition in the basin and is interpreted to have been deposited during a relative highstand in sea level. The lowstand systems tracts are composed dominantly of quartz sandstone, commonly intercalated with carbonate debris beds at the toe of the slope. Sequence boundaries display erosional truncation (subaerial on platform or at platform margin, subaqueous on slope) and/or subaerial exposure. Erosion and debris deposition occurs both within and outside submarine-canyon feeder systems.

Two highstand depositional styles are differentiated here: (1) a keep-up system, which represents a relatively rapid rate of accumulation able to keep pace with periodic rises in sea level and displays a mounded-oblique stratal geometry at the platform margin, and (2) a catch-up system, which represents a relatively slow rate of accumulation and displays a sigmoid profile at the platform margin. Individual strata units of the platform margin and slope area of the catch-up carbonate system have a much longer sea-floor residence time and display significantly greater amounts of early submarine cement. The underlying transgressive systems tract tends to have a keep-up or give-up (i.e., thin, drowned) depositional style.

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Carbonate Platforms, Sequence Stratigraphy, and Sea Level

Besides tracing reflectors, the mapping of stratigraphic sequences marks a major advance in seismic interpretation. However, construction of sea level curves from sequence stratigraphy is complicated by other factors besides sea level influencing sequence geometry. One such factor is lithology. This point is examined by comparing siliciclastic systems and carbonate platforms.

During the Pleistocene, the siliciclastic sediment supply to the deep sea was at its maximum during glacial lowstands of sea level. Pleistocene carbonate platforms were exactly in antiphase to this rhythm. They produced and exported most sediment during interglacial highstands when the platforms were flooded ("highstand shedding"). In the Bahamas and other platforms, accumulation of both bank-derived fines and sandy turbidites is higher by a factor of 2 to 9 during the interglacials, and turbidites tend to cluster in these highstand intervals. Highstand turbidites also differ in composition from their lowstand counterparts. Turbidite abundance and composition together provide a faithful record of the Pleistocene sea level cycles not easily erased by diagenesis. Geometrically, platforms respond to sea level by forming highstand turbidite wedges and lowstand drapes of pelagic sediment—the opposite of siliciclastic systems.

Drowning unconformities are another example for the significance of lithologic change in sequence stratigraphy. Flanks of carbonate platforms are generally steeper than siliciclastic slopes. When carbonate platforms are drowned and buried by siliciclastics, an unconformity ensues because the clastics are unable to assume the steep carbonate slope angle or because they are shed from other directions than the carbonates. Examples of drowning unconformities include the Lower Cretaceous platforms off West Africa and off eastern North America as well as the middle Cretaceous unconformity in the Gulf of Mexico.

Highstand shedding and drowning unconformities of platforms illustrate that not all depositional systems respond alike to changes in sea level and that sequence boundaries may be caused by lithologic change. These lithologic turning points need not be related to sea level. In a very general way, sequence boundaries can be viewed as changes in the pattern of sediment input and dispersal in a basin. Sea level fluctuations are one way to induce such changes, but tectonic movements and environmental change represent important alternatives, demonstrated by the seismic stratigraphy of the deep Gulf of Mexico.

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Reservoir Description for Exploration and Development: What is Needed and When?

The biggest challenge for geologists, geophysicists, and petroleum engineers now and in the decades ahead is to significantly improve hydrocarbon recovery from all new and previously discovered reservoirs. Keystone of the methodology required to improve oil and gas production, as well as to evaluate and delineate new reserves, is a detailed reservoir description. This is a characterization of the reservoir and nonreservoir rock-fluid system that is appropriate in content and detail for the particular stage of exploration and production. The type and amount of data required for a proper reservoir description are diverse, from several disciplines, and depend upon the stage of the reservoir's exploration and production cycle. The cycle is viewed as a continuous series of overlapping stages from discovery, through appraisal, planning, development, and reservoir management. The concepts and data needed to define and exploit reservoirs become more complex and quantitative as the production becomes more mature. Concepts, data, and models developed during the production phases, when reapplied to exploration, provide important guides to the explorationists for evaluating trapping elements, seals, reservoir quality, and risks in basin and wildcat evaluation.

When one looks at the question "When is a reservoir description needed?" the answer is simple. The need starts once a discovery is made and the discovery is being appraised as to the best estimates of hydrocarbon in place, recoverable reserves, and production rates. As a field or reservoir goes through its typical cycle of discovery, appraisal, planning, development, and reservoir management, a more complete description is both necessary and possible.

A critical first step in the reservoir description process is recognizing any correlative reservoir subzones or layers and any intervening dense, impermeable, or low-permeability strata. Knowledge of the depositional/diagenetic processes controlling reservoir and nonreservoir rock is essential to determine one's ability and degree of confidence in correlating these units. Seismic sequence, lithologic, and fluid analyses, and well-documented outcrop studies can add significantly in establishing interwell correlations. Recognizing and mapping all vertical or horizontal fluid-flow barriers, as well as theif zones or zones of unusual permeability contrast and faults, are critically important to all recovery processes. Flow-test data dovetailed with knowledge of the reservoir and nonreservoir framework based on geology/geophysics provide the best reservoir description of continuity/discontinuity.

Structural and stratigraphic maps, cross sections, and fence-and-block diagrams convey the three-dimensional geometry, distribution, and continuity of the reservoir, nonreservoir, and aquifer. A variety of computer programs aid in preparing these illustrations. Isopach maps without the accompanying detail correlation sections have been the pitfall of many projects. Net-pay isopach maps drawn to provide the basis for determining hydrocarbons in place have tricked many petroleum engineers into believing a reservoir is more continuous, more homogeneous, and less stratified than it actually is.

The importance of discontinuous shale barriers of limited areal extent on coning and the drainage of oil from a gas-invaded area illustrate the need to include shale dimensions in many types of recovery calculations and predictions.

The recognition, selection, and description of reservoir units or layers, and the communication of this picture to the petroleum engineers are fundamental contributions and responsibilities of the geologists/geophysicists. A coordinated data-acquisition program can greatly improve the probabilities of correct assessments in discovery, appraisal, planning, development, and reservoir management.

A good reservoir description designed to answer key reservoir performance questions is a fundamental tool. The incremental well costs to obtain adequate data for a reservoir description are very small compared with its value in improved recovery. The time to complete a reservoir description is before significant expenditures are planned and spent. Mathematical models and simulation of reservoir performance that do not have a realistic reservoir rock–fluid description are interesting, but are expensive exercises that potentially lead to inappropriate or incorrect management decisions.

In exploration ventures, detailed reservoir-description studies made during the production stages provide the critical data needed by the explorationist to estimate reservoir and seal quality from seismic, well logs, and samples.

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Laramide Basin Subsidence and Basement Uplift in Rocky Mountain Foreland of Wyoming

The basement-cored ranges of the Rocky Mountain foreland have attracted geologists' attention since the time of early exploration of the western United States and have been the subject of numerous structural studies since early in this century. Until the advent of hydrocarbon exploration, however, the basins got little attention. Even today, our knowledge of the uplifts far exceeds that concerning basin genesis. The most recent work shows that uplift of the ranges and subsidence of the basins are intimately related and suggests that viewing the subsidence-uplift couple as the unit of deformation in the foreland is most likely to lead to a better understanding of the timing and kinematics of the Laramide orogeny.

The Wind River Range in western Wyoming is an excellent natural laboratory for studying a Laramide uplift. A COCORP seismic profile provides geometric control, and tectogenic sediments record the history of uplift and erosion. The stratigraphy and provenance of these sediments indicate a complex Laramide and later tectonic history for the range and identify the timing and position of individual faulting events. These events are (1) main uplift of the range by motion on the Wind River fault and the formation of an erosion surface of low relief (Late Cretaceous through early Eocene), (2) elevation of this erosion surface as much as 3,000 ft (914 m) by motion on imbricates and associated tear faults in the hanging wall of the Wind River fault (end of early Eocene), (3) collapse of the tip of the Wind River fault into sedimentary fill of the Green River basin (between middle Eocene and late Oligocene), (4) uplift of the crest of the range by nearly 3,000 ft (914 m) forming the highest peaks in the Wyoming foreland (late Oligocene), and (5) collapse of the southern part of the range along normal faults (Neogene).

Basin modeling in two distinctly different structural settings points to several driving mechanisms for subsidence in Laramide basins. Subsidence of the northern Green River basin was a flexural response to sediment loading and the intracrustal and topographic loads imposed by uplift of the adjacent Wind River Range. In contrast, the Hanna basin subsided when a rigid crustal block rotated downward as the Rawlins uplift was raised on the other end. Both flexure and rigid block rotation likely are operative to varying degrees in most Laramide basins.

A schematic cross section through central Wyoming suggests that deep basins, where both rotation and tectonic loading are important, support structurally low ranges. Where rotation is not an important component of subsidence, basins support structurally high ranges. Furthermore, because basin subsidence and basement uplift are genetically linked, both indicate the timing of Laramide deformation.

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Pore Throats to Plate Margins: An Integrated Approach to Basin Analysis

The basin analysis approach to modeling sedimentary basins affords the opportunity to view ore deposits or accumulations of fossil fuels in the context of the evolution of the entire basin. Integration of data from diverse specialties is now widely practiced, and the multidisciplinary approach to the study of basins has greatly enhanced our ability to understand and to predict the occurrence and distribution of economically important commodities.

A significant outgrowth of the basin analysis technique is a more rigorous testing of scientific paradigms. Feedback from diverse specialties provides numerous constraints so that no conclusion can be drawn about one aspect of a basin's history without affecting the interpretation of other aspects. Thus, when a conclusion from one line of evidence is at variance with a conclusion drawn from several other lines of evidence, it is necessary to challenge the assumptions that led to the different conclusions. Challenging such assumptions usually involves examining cherished theories or paradigms. Our general reluctance to discard prevailing theories reflects our heavy reliance on useful rules of thumb; without them we could not begin to interpret the geologic past. This reluctance to relinquish useful theories is more easily overcome when several lines of evidence point us toward new concepts that have exciting implications of their own. Basin analysis, by its very nature, pushes us toward new perspectives and thus serves to promote new discoveries in geoscience.

A case study in the San Juan basin of New Mexico serves as an example of the basin analysis approach to a geologic problem and serves to illustrate that sometimes answers to questions that were never posed are the most significant (and surprising) outcome of the basin-analysis approach. The original goal of the San Juan basin study was to develop a genetic model for sandstone-type uranium deposits in the Jurassic Morrison Formation. Tectonic, geophysical, sedimentologic, petro-