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Dealing with Risk and Uncertainty in Exploration: How Well Do We Predict? How Can We Do Better?

Risk and uncertainty are inherent aspects of investing in exploration ventures. Risk, the weight of investment with respect to budget and consequence, is a subtle, variable, but important factor that is intrinsically difficult to apply consistently. Uncertainty, the perceived range of probabilities that a given situation may exist, lends itself more readily to systematic consideration. Professionals may be able to improve their ability to assess uncertainty more reliably. Judgments of both risk and uncertainty are highly susceptible to psychological influences and biases of which most explorationists are unaware.

Two of the most influential considerations involved in exploration decisions are (1) the likelihood that a postulated hydrocarbon accumulation is present, and (2) the probable volumes of oil or gas contained in the prospect if it exists. Both lie within the geotechnical purview. Such exploration predictions are made routinely, and they have enormous financial impact. Nevertheless, few public data have been available as to actual performance records of explorationists' predictions: many organizations do not examine predictive performance, and the few that do are reluctant to publicize their records. The reasons are mostly human and understandable, relating to the forward press of exploration events, individual chagrin, corporate politics, proprietary advantage, and even professional modesty.

Limited data on predictive accuracy in exploration began to be available in 1979 and suggest the following general patterns.

1. Accuracy of hydrocarbon-volume forecasts ranges widely, based on predrilling and postdrilling estimates; there may be roughly a 90% chance that a given volumetric forecast will be accurate within about one order of magnitude (power of ten), plus or minus the actual volume of the accumulation.
2. Forecasts of hydrocarbon volumes tend to be overly optimistic. The chief technical reason has to do with erroneous predictions of hydrocarbon recovery factor. Other nontechnical forces also appear to contribute to this trend, including motivational bias.
3. Analysis of various geological risk factors (such as structure, reservoir, trap, or charge) may help improve assessment of discovery probability; however, prior to drilling a prospect, explorationists commonly do not identify which geological factors constitute the primary exploratory hazards. Also, many explorationists confuse "exploratory success" and "commercial success."
4. The dedicated technical intellect is loath to recognize and accept the large uncertainties and biases actually involved in his/her professional predictions and, therefore, may encourage exploration management to make unwarranted expenditures for data prior to drilling. This tendency is reinforced by the natural corporate inclination to reduce exploratory uncertainty to a minimum prior to drilling.

Growing evidence exists that professional exploratory performance can be improved through the following.

1. Training to minimize heuristic biases inherent in estimating uncertainty, as well as decision-making in risk ventures.
2. Postmortem analysis of exploration predictions and decisions.
3. Evaluation of tactics versus declared strategy, by comparing various exploration parameters (e.g., discovery probability, predicted target volume, actual discovered volume, finding rate, working interest, and prospect origin).

Discerned performance trends can then be used to discount or enhance new prospects, to highlight areas for future improvement, and to modify corporate stances and strategies. Such analysis may best take the form of individual professional progress, rather than imposed management inspection.

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Predictive Models for Sandstone Diagenesis

The maturation of organic material in hydrocarbon source rocks and inorganic diagenetic reactions in reservoir sandstones are a natural consequence of the burial of a prism of sedimentary rocks. The distribution of porosity/permeability enhancement in potential hydrocarbon reservoirs can be predicted by integrating the reaction processes characterizing the progressive diagenesis of a reservoir/source rock system.

A variety of observations suggests that the organic solvents necessary to increase aluminosilicate and carbonate solubilities in sandstones can be generated either by thermal or oxidative cracking of carbonyl or phenolic groups from kerogen in adjacent source rocks. For example, nuclear magnetic resonance (NMR) spectra of kerogen show that peripheral carbonyl and phenol groups are released from the kerogen molecule prior to the generation of liquid hydrocarbons.

Experimental data indicate that these water-soluble organic solvents can significantly affect the stability of both carbonate and aluminosilicate minerals. Water-soluble organic acids (carboxylic) have been observed in oil field waters in concentrations up to 10,000 ppm, and they commonly dominate the alkalinity in the fluid phase over the 80°-120°C temperature range.

The integration of the organic and inorganic diagenetic reactions can be modeled conceptually by constructing a series of potential reaction pathways with increasing temperature, for a system that includes aluminosilicate minerals, carbonate minerals, organic solvents (carboxylic and phenolic), and carbon dioxide. The important chemical divides in these diagenetic flow diagrams are dependent on temperature, the nature of the buffer in the carbonate system (internal or external), and the relationship between organic acids and P_{CO_2}. Forward predictive capabilities result when this general diagenetic model is placed in a time-temperature framework. The detailed organic and inorganic geochemistry and the general thermal scenario used in the time-temperature analysis must be basin-specific. Casting the diagenetic history of a sandstone into this type of process-oriented model enables one to make the transition from a conventional descriptive mode to a predictive mode of analysis.

Predictive models have been developed for several tectonic settings, including rift or "pull-apart" basins, and intermontane or "Laramide" basins. From these reconstructions, two types of information result: (1) general optimum conditions for porosity/permeability enhancement in sandstones are delineated, and (2) specifically, the degree and potential for porosity/permeability enhancement are determined. Forward prediction of the porosity-enhancing potential of a diagenetic system is possible based on an understanding of the reaction processes in a time-temperature framework.

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Paleogeographic Evolution of China

China presents a challenge to the paleogeographer because all but 9% of this huge country has been tectonically deformed between the Jurassic and the present. Even the undeformed areas—the Sichuan basin of south China, the Ordos basin of north China, and the Tarim and Dzungarian basins of west China—have thrust-loaded margins. The present geometry of China resulted from the accretion to Asia during the late Paleozoic to the early Cenozoic of three moderate-size continents (Yangtze, Sino-Korean, and Tarim) as well as numerous smaller continental fragments in the region of the Tibetan Plateau. As might be expected, the present collision pattern of India with Asia and the resultant thrusting of western China and "continental escape" of eastern China by transtensional systems became manifest during some of these earlier collision episodes.

Is there any hope of "untying the Gordian knot" and reconstructing this complicated history with any confidence? Chinese geologists have been able to date the collisions of the constituent microcontinents by studying the ophiolite and flysch sequences. Their biogeographic studies would point to Gondwana as the most likely source of these continental elements. Also, Chinese geologists have been assiduous in describing the rich stratigraphic record of their country, so it is possible to deduce from the distribution of the climatically sensitive sediments the approximate paleolatitudes of the microcontinents during their transits of Tethys. This information can be compared with paleomagnetic results that are just becoming available. The sea-floor-spreading history of the Indian Ocean provides some constraints, but prior to the collision of India in the Eocene, China was completely surrounded by subduction zones and therefore detached from the ocean floor.

The general picture then is the accretion in succession, from north to south, of microcontinents, of which India is the most recent arrival. Left-lateral deformation between and within these elements was a recurrent pattern from the Jurassic onward. Subduction zones formed on the southern and eastern margins of the accreting Asian continent, but the eastern arcs were of an extensional nature. The timing of this back-arc extension varied from place to place, i.e., Late Jurassic in the Songliao basin of northeast China, Cretaceous in the basin-and-range-type extension in southeast China, and middle to late Tertiary in the Japan Sea, Bohai, Subei, East China Sea, and South China Sea basins of the entire eastern perimeter of the continent.

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Evolution of the Arctic-North Atlantic Rift System

The Arctic-North Atlantic rift system is superimposed on the Caledonian and Hercynian sutures of Laurentia-Greenland, Fennosarmatia, and Africa.

Devonian to Early Carboniferous wrench movements along the axis of the Arctic-North Atlantic Caledonides preceded the late Visean onset of crustal extension on the Barents Shelf and in the Norwegian-Greenland Sea. These rifts remained intermittently active for about 270 m.y. until crustal separation between Greenland and Fennosarmatia was achieved during the early Eocene. The Carboniferous rifts of the British Isles and the Canadian Maritime Provinces became inactive during the late Hercynian diastrophism, during which they were deformed to varying degrees by transpressional movements.

The Triassic development of the Tethys-Central Atlantic-Gulf of Mexico rift-transform system was accompanied by rift propagation into the North Atlantic and west European domain, whereby the reactivation of late Hercynian wrench faults probably was an important factor in the localization of individual grabens. The development of the North Sea and West Shetland-Rockall-Lusitania-Grand Banks rift system is probably related to the Late Permian and Triassic southward propagation of the Norwegian-Greenland Sea rift system.

Following crustal separation in the Tethys during the Middle Jurassic and in the North Atlantic during the Early Cretaceous, the rifts on the respective continental margins became inactive, while crustal extension continued in areas north of the Charlie-Gibbs fracture zone. Particularly in the Norwegian-Greenland Sea area, a gradual concentration of rifting activity toward the future zone of crustal separation can be observed. This activity was accompanied by a decrease of rifting in marginal graben systems, such as those of the North Sea and the Barents Shelf. After the early Eocene crustal separation in the Iceland and Norwegian-Greenland Seas, grabens on the adjacent shelves became inactive.

The duration of the rifting stage preceding crustal separation is highly variable (Central Atlantic ±50 m.y., Norwegian-Greenland Sea ±270 m.y.). Volcanic activity in the Arctic-North Atlantic rift was generally at a very low level during its Paleozoic and Mesozoic evolution, but increased prior to crustal separation. Evidence shows that intermittent local thermal doming is possibly related to the implacement of hot asthenospheric material in the upper mantle, at the crust-mantle boundary, and/or within the lower crust.

The hydrocarbon potential of the various branches of the Arctic-North Atlantic rift system is highly variable. Source rock and reservoir developments are controlled by the paleogeographic setting of the respective basin, whereas their preservation and the development of effective hydrocarbon kitchens are largely related to the geodynamic process governing the subsidence-uplift of the respective basin.

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Smectite Dehydration—Its Relation to Structural Development and Hydrocarbon Accumulation

A comparison of clay diagenesis data obtained from a study of Tertiary shales from wells drilled in the Brazos-Colorado River system of Texas, the Mississippi River system of Louisiana, and the Niger River system of Nigeria illustrates significant differences in temperature intervals over which smectite (expandable clay) diagenesis occurs.

The age of the shales studied ranges from 1 to 50 m.y., and the threshold temperature required to initiate diagenesis ranges from about 160°F (71°C) in Mississippi River sediments to more than 300°F (150°C) in the Niger delta. Water expelled from smectite into the pore system of the host shale during the process of diagenesis may migrate out of the shale early, or it may be totally or partially trapped and released slowly through time. In either situation, the water can act as a vehicle for hydrocarbon migration provided hydrocarbons are present in a form and in sufficient quantities to be transported.

Observations from the northern Gulf of Mexico basin indicate a close relation between buildup of high fluid pressure and the smectite-illite transformation process. Abnormal pressures exert partial control on the type and quantity of hydrocarbons accumulated because pressure potential determines the direction of fluid flow, and overpressuring partly controls the geometry of growth faults and other related faults and folds in the basin.

The depths to which growth faults can penetrate and the angle of dip that these faults assume at depth are largely dependent on fluid pressure in the sedimentary section at the time of faulting. Dips of some faults in Texas have been observed to change abruptly within the interval of smectite diagenesis, and some faults formed in the overpressured Miocene and younger sections become bedding-plane types at depths above the temperature level required for thermal generation of petroleum. Although these faults are important for fluid redistribution in the shallow sandstone-shale section, they play a minor role in moving hydrocarbons out of shales below the faults in much of the Texas offshore area.

Fluid movement upward along fault systems in the lower Tertiary section, which overlies fault trends in the sub-Tertiary section, is proposed as a mechanism for flushing hydrocarbons from the deeper portion of the northern Gulf of Mexico basin. These fault systems would have maximum development immediately above the "basement faults," with displacement decreasing progressively upward. Seismic data indicate that, in the upper (younger) Tertiary section, these deep fault systems are represented by near-vertical (high-angle) fracture systems that cut across the low-angle growth faults. Fluid movement within these deep fault and fracture systems would be enhanced by smectite diagenesis because water derived from smectite that was trapped during basin subsidence would cause the flushing process to continue for longer periods of time and to extend to greater depths than could be attained if only remnants of original pore water were present.

Based on data obtained from both the Brazos-Colorado and Mississippi River systems, it is concluded that smectite dehydration in shale is a major factor in both hydrocarbon migration and accumulation in basins where expandable clays are present. Concepts developed here can be applied to any basin that has had or now contains expandable clay shales. The effect of smectite diagenesis and the time of fluid release out of the shales must be considered with all other stratigraphic, structural, and geochemical parameters considered in basin evaluation.

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Theoretical Aspects of Cap-Rock and Fault Seals for Single- and Two-Phase Hydrocarbon Columns

Cap-rock seals can be divided genetically into those that fail by capillary leakage (membrane seals) and those that fail due to fracturing or wedging open of faults (hydraulic seals).

A given membrane seal can trap a larger column of oil than gas at shallow depths, but at greater depths, gas is more easily sealed than oil. Where a gas cap overlies on oil rim, however, the maximum-allowable two-phase column is always greater than if only oil or gas occurs below the seal.

This trap contrasts with the hydraulic seal, where the seal capacity to oil always exceeds that for gas. Moreover, a trapped two-phase column, at hydraulic seal capacity, will be less than the maximum-allowable oil-only column, but more than the maximum gas-only column.