

Plate tectonics and petroleum basins

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Abstract: The formation of basins and associated petroleum habitats can be explained in terms of the fundamentals of plate tectonics. Of all the basin types, plate-margin foreland basins are the most prolific hydrocarbon settings. In these basins, the organic-rich source rocks are deposited **prior to** continental collision. The effects of the younger collision result in both foreland sedimentation, which stimulates petroleum maturation in buried sediments, and the architecture of foreland basins, which provides a safe haven for huge accumulations of both oil and gas. In all the other basin types, either reflecting intracontinental convergence, continental sags over aborted rifts, continental rifting or translational motions, the oil habitat, from source to reservoir, is wholly within the formation cycle of the individual basins.

INTRODUCTION

By developing models that integrate the principles of plate tectonics with the requirements for the formation of petroleum accumulations (rocks that provide reservoir, source, and seal and the processes of maturation, expulsion, migration, and entrapment) we are able to gain a sense of the efficacy of published worldwide resource estimates as well as an insight into areas that might be underexplored, particularly for natural gas resources.

Attempts to relate petroleum occurrences to specific plate-tectonic settings are, however, hampered by (a) the existence of a variety of basin classifications — a problem of concepts, not necessarily of nature — and (b) the superposition through time of different tectonic settings at any given petroleum province — an example of nature changing faces through time (for example, the Tertiary foreland basin of the Persian Gulf is superimposed upon a late Paleozoic-early Mesozoic rifted continental-margin).

Numerous basin classification and basin formation schemes have been offered in the literature to define the habitat of petroleum occurrences. Many classifications are seemingly tailored to specific settings while others are intended to be global in concept. Classifications based on plate tectonic settings are useful in explaining how basin geometries, kinematic histories and dynamic forces are mutually integrated. Using the U.S. basins as a template, and looking at basins world wide, one sees how plate tectonic processes affect the development of petroleum habitats.

RIFT SETTINGS

The Gulf of Mexico represents a continental rift basin; other examples world wide include Campos, Niger delta, Sirte, North Sea and the South China Sea *sensu strictu*, albeit I will suggest below that the latter is a local extensional feature in a regional transcurrent setting. Source rocks in all rift settings accumulate in lake beds or anoxic silled marine troughs during early phases of rifting. Salt, another rock type formed during the early phases of rifting is an important element making up seals and contributing to structural closures as the salt becomes allochthonous. Other trapping mechanisms are associated with rift-related structures and the displacement of gravitationally unstable sediments that accumulate during the drift phase of rifted margins.

Rifting is also responsible for continental sags, such as the Illinois basin or the West Siberian basin. These basins overlie regions of aborted continental rifting during which the lower crust was tectonically thinned and invaded by dense mantle material, both processes effecting regional subsidence within the craton.

TRANSCURRENT MARGINS

The basins along the California margins reflect the formation of basins associated with transform motion between two plates; other worldwide examples include the Bohai and Dajing basins of eastern P.R. China. Crustal thinning attendant with transpressional tectonic movements result in rapid subsidence. These basins are commonly silled,

promoting the accumulation and preservation of source rocks. With minor changes in plate motions or where faults bend, the crust may be exposed to transpressional forces which create structural closures as the basins evert.

On a more controversial perspective, the whole of the archipelagic region of the south Pacific, the basins, ridges, shoals and islands between the Andaman-Sunda trenches on the west and the Philippine trench on the east, may be considered a mega-transcurrent setting. The fundamental shear is between the Indian Plate on the west and the Pacific Plate (including the Philippine Sea Plate) on the east. In the early Middle Tertiary the entire region experienced transtensional shear which brought about the formation of basins, region-wide. Many of these basins remained non-marine while others evolved into deep marine settings. By the late Tertiary local transpressional conditions began to form structures, particularly along the margins of small block rotations. The kinematics of these individual blocks remain poorly understood or at least uncertain and controversial. By viewing the region as a whole, however, a seemingly simple scheme of transcurrent shear provides a geodynamic content consistent with the principles of plate tectonics.

CONVERGENT SETTINGS

The foreland basins of the Rocky Mountains and the various foreland settings cratonward of the Appalachian-Ouachita-Marathon orogen reflect the two most common types of hydrocarbon settings stemming from convergent tectonics. For the first type, convergent stresses are transmitted within the lithosphere a long distance from any plate margins; other examples worldwide include the Tarim, Jungar, Ordos, Sichuan, Neuquin, Oriente, Ebro and Aquitaine basins. The second type of convergent basins are those that lie along plate margins and reflect collisional tectonics; examples worldwide include foreland basin regions of the Persian Gulf, Ural-Volga, North Slope, and sub-Andean basins.

A third, seemingly anomalous, convergent-type basins are the so-called impactogens. These basins lie some distance away from regions of collision, on either the upper or lower lithospheric plates, and are oriented parallel to the direction of maximum stress; i.e. crustal extension is perpendicular to the direction of convergence. Lake Baikal (north of the Himalayan orogen) and the Rhine graben (north of the Alpine orogen) are examples, albeit neither are prolific hydrocarbon habitats.

Source rocks of intermontane basins are generally, but not exclusively, organic-rich

lacustrine debris that accumulated contemporaneously with basin subsidence. Conversely, plate-margin forelands are generally built across an older passive margin containing immature, organic-rich marine strata that accumulated prior to the episode of convergent tectonics. In most foreland basins, expelled oil and gas may migrate into the fold and thrust portion of the orogen, but the largest accumulations of oil occur near the peripheral bulge on the continent side of the foreland basin. Where foreland basins are superposed over preexisting deep basins, major gas plays exist. Examples include preexisting aulocogens, such as at Anadarko, and preexisting rift basins, such as at the Qatar play.

The principal habitat for the world's petroleum resources (including tar sands and heavy oils) is fold-and-thrust belts and their associated foreland basins. The rationale is simply that the petroleum generation process follows a predictable scenario as a consequence of the continental compressional event and the resulting thickening of the continental crust.

In order to create the petroleum habitat of fold-and-thrust belts and foreland basins the plate tectonic phenomenon of continental shortening is required. Such a tectonic regime may be **triggered** by any of three distinct plate tectonic events: (1) accretion of one or more volcanic arcs to a continental margin, (2) the collision of two continents, or (3) movement of a continental mass over a very gently inclined oceanic lithosphere (so-called flat-slab). The first situation has produced such features as the Brooks Range and much of the Cordillera of North America; the second has produced features such as the Appalachian-Ouachita-Marathon, Zagros, Alpine-Himalayan and Ural orogens; and the third is reflected by parts of the late Tertiary Andean orogenic belt of South America.

Sub-sets of these collisional zones are instances where compressional forces extend far into a continental domain effecting intracontinental shortening (or A-subduction), as displayed by the various mountain ranges bounding the basins of western China (e.g., Sichuan, Tarim, and Jungar basins), Andean intracontinental shortening (e.g., Cuyo, Oran, and Magalanes basins), or the Laramide basins of the western interior of USA. (for example, Denver, Powder River, Piceance, Wind River, and Big Horn basins).

Regardless of which of these three plate tectonic settings leads to continental shortening, the style of continental crustal deformation is essentially identical. For these settings to be petroliferous, the critical ingredient is the preposition of a regionally extensive, thermally immature, organic-

rich source rock on an older platform or passive continental margin. These pre-existing source rocks are generally, but not exclusively, Ordovician, Devonian, Triassic, Jurassic, and/or Cretaceous black shales. Additionally, platforms and passive margins are ideal settings for the deposition of potential reservoir strata, for example, quartz-rich sandstones or carbonate banks and reefs. Thus, the superimposition of a tectonic orogen across an older platform or passive continental margin is the critical requirement in the production of the vast majority of the world's petroleum. The platforms and passive continental margins house both the reservoir and source rocks while the superposed orogens effect maturation and create the architecture for hydrocarbon migration and entrapment.

Tectonic thickening in the orogen imposes a crustal load that produces a crustal sag (the foreland basin) and a lithospheric bulge that defines the outer margin of the foreland basin. The sedimentary fill of the foreland basin creates a thermal blanket that effects petroleum maturation; additionally, the architecture of the foreland provides pathways towards the lithospheric bulge, above and beyond which vast quantities of oil can accumulate. Secondly, the lithofacies of foreland strata consist of rapidly deposited, laterally discontinuous clastic strata that may produce excellent stratigraphic traps.

The expulsion of petroleum from source rocks is generally thought to range from 10 to 25 percent of the total amount generated, although some authors have suggested models with up to 80 percent expulsion. After oil migration the foreland basin continues to receive sediments, although much of the still-rich source rock is depressed far below the oil generating window. Therefore, natural gas becomes the primary hydrocarbon generated in the orogen and deeper parts of the foreland basin in the later stages of the orogenic cycle. The principal limiting factor in this late-stage generation of gas is the amount of hydrogen available with the extant oil and source rock. The small size and ease of

diffusivity of the methane gas molecule allow the gas to migrate vertically into structures and stratigraphic traps located in the proximal, orogenically cannibalized part of the foreland. In young, still-active systems, such as the Zagros-Persian Gulf province, oil may remain preserved in the fold and thrust part of the system, as evidenced by the extensive oil resources in Iran and northern Iraq. But in fully developed orogenic areas, the consequence of multiple deformational events in the fold-and-thrust belt is the destruction of the early-formed traps and seals. Thus, the initially-trapped oil may remigrate to new traps or may be lost to the surface. In the new configuration, these areas become gas habitats, the flux of gas being introduced after the initial migration of oil. In tectonically mature fold-and-thrust belts, one would expect to find primarily oil accumulations in regions distal from the orogen and primarily gas accumulations in regions proximal to the orogen. The Appalachian-Ouachita-Marathon system characterizes such a mature setting with gas provinces in the deformed part of the foreland and oil in the distal, little-deformed part of the foreland.

Numerous local variations to this generalized pattern can account for important petroleum accumulations. Tectonic inversions of the superposed passive, continental-margin structures can create traps such as the Ghawar field in Saudi Arabia, and syn-orogenic shale of the foreland basin may also source structures in the fold and thrust belt as demonstrated by the Umiat oilfield on the North Slope of Alaska. Nonetheless, armed with this simple petroleum-tectonic model, much of the world's known petroleum resources can be explained and relatively unexplored regions such as the foreland areas of Tian Shan, Kunlun, Himalaya, and the southern Andes can be more effectively evaluated. The greatest uncertainty appears to be the amount of methane that is yet to be discovered. The analysis presented here suggested that fold-and-thrust belts, even well into the internal zone of the orogen, are potential sites for late stage natural gas accumulations.