U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

OPEN-FILE REPORT 2006-1172
Version 1.0

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Potential Tight Gas Resources in a Frontier Province - Jurassic Through Tertiary Strata Beneath the Brooks Range Foothills, Arctic Alaska.

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2005

Abstract

Beneath the foothills of the Brooks Range, rocks of the Lower Cretaceous-Tertiary Brookian and Jurassic-Lower Cretaceous Beaufortian megasequences have been deeply buried and exhumed, and now exhibit characteristics of "tight gas sandstones". The data recovered from drilling, well tests, and cores exhibit the potential for substantial gas reserves over a large area. These data include recovery of gas from drillstem tests, indications of overpressure from well tests and mud weights, low porosity and permeability in sandstones, and vitrinite reflectance values ranging from 1.0 to 2.0 percent throughout substantial depth intervals.

Brookian and Beaufortian Megasequences

Jurassic through Tertiary strata beneath the Brooks Range foothills comprise two major overlapping tectonostratigraphic megasequences. The Jurassic-Lower Cretaceous Beaufortian megasequence (Kingak Shale) is an offlapping depositional succession that prograded southward (present coordinates) during rifting and opening of the Arctic Ocean basin to the north. The Lower Cretaceous-Tertiary Brookian megasequence consists of a series of depositional sequences derived from the Brooks Range and deposited to the north in the Colville Foreland Basin, which was progressively filled as clastic systems prograded eastward and northward.

Both the Beaufortian and Brookian megasequences generally display similar vertical successions of facies, including in ascending order (1) a basal condensed section that includes low-velocity shales with good to excellent source-rock character, (2) a base-of-slope succession that is mostly marine mudstone in the Beaufortian megasequence and that includes marine mudstone plus turbidite-sandstone facies in the Brookian megasequence, (3) a relatively thick marine slope section consisting of mostly mudstone, and (4) a marine shelf-to-shore system that includes sandstone and mudstone. In the Brooks Range foothills, these coarsening-upward megasequences are stacked vertically, with the Beaufortian megasequence as thick as ~4,000 ft and the Brookian megasequence as thick as ~20,000 ft. Even greater thicknesses are expected southward toward the Brooks Range, where structural deformation has produced stacked sections.

Structure and Geologic Sections

The structure section (right) spans the entire Brooks Range foothills province. This section, based on seismic interpretation supplemented by surface geologic field studies and a few well penetrations, shows the overall basin geometry, major stratigraphic units, and pattern of faulting. The section is long and narrow because it is shown without any vertical exaggeration in order to correctly portray structural geometry and attitudes. The geologic section (below right) is also based on seismic but is limited to the more northern part of the region where well data are available. A vertical exaggeration of about 16x is used to show details of stratigraphy, well log responses, hydrocarbon occurrences (shows), and pressures.

Reservoir Geometry

Potential tight-gas reservoirs consist mostly of amalgamated sandstone facies deposited in turbidite fan and channel systems in a base-of-slope setting. Sandstone thicknesses and lateral extent of these facies are variable, although Beaufortian sandstones are poorly known because of limited well penetrations. In contrast, Brookian sandstones are known from both outcrops and well penetrations, and gross thicknesses of sandstone-prone successions typically range from 2,000 to 6,000 ft in the deep basin. Within this gross interval, stacked sandstones comprising hundreds of feet of potential reservoir have been observed (for example, Tulugak well). Seismic data and sparse well data indicate imply that coalesced fan systems have lateral dimensions of tens of miles.

Overpressure Mechanisms

A number of mechanisms for generating overpressure have been described in the literature (see Martinsen, 1994, for a summary). Four mechanisms could play a role in the strata considered here: (1) nonequilbrium compaction, which requires rapid deposition and low permeability rocks; (2) hydrocarbon generation, which produces fluid volume increases; (3) tectonic compression, which requires horizontal compressive stresses of magnitude comparable to or greater than vertical stress; and (4) uplift of isolated compartments, which requires maintenance of pressure seals. Conditions for these four mechanisms all appear to be present in the deep Colville Basin, and all four could be contributing in some measure to the observed overpressure; however, at present we are unable to assess their relative importance.

Here we pose a question regarding the role of gas pressure in the early Tertiary deformation illustrated on the structural cross section: did gas generation in the Kingak Shale during Cretaceous to early Tertiary time cause high pore pressures, which allowed early Tertiary deformation to occur preferentially in the Kingak Shale?

Extent of Tight Gas Potential

Evidence of undercompaction, gas charge, and overpressure in Brookian and Beaufortian rocks extends nearly the entire length and breadth of the Brooks Range foothills region, an area of approximately 40,000 square miles. Although the volumes and locations of tight gas accumulations are unknown, some of these undiscovered gas resources may lie in close proximity to a proposed natural gas pipeline, the route of which will likely parallel the Trans-Alaska Pipeline System.

Elevated Mud Weights Constrain Overpressure Estimates

In this graph, mud weights used in individual wells have been converted to an equivalent pressure in pounds per square inch. For example, a mud weight of 10 pounds per gallon produces a pressure gradient of 0.52 psi/ft, exerting a pressure of 5,200 psi at 10,000 ft. Pressures in Brookian rocks are linked with dashed lines, and in Beaufortian rocks with heavy solid lines; pressures in Ellesmerian rocks are not shown. Wells in the foothills (red symbols) and in the transition between foothills and coastal plain (blue symbols) required substantially higher mud weights to control subsurface pressure than wells located to the north in the coastal plain (green symbols). Depth plots of mud weight, well logs, and drillstem test results for selected individual wells are displayed on the next panel.

Permeability and Porosity are Low

Data from Brookian rocks in the accompanying table show that average porosity is around 10 percent, permeability is less than 1.0 millidarcy and commonly less than 0.1 millidarcy, based upon conventional (unconfined) core measurements. Descriptions of samples from these same intervals indicate that sandstones are well consolidated and very fine to fine grained. The gamma-ray log in the Tulugak well is typical of other penetrations of Brookian sandstones and siltstones where gamma-ray levels range from 40 to 80 API units. Reservoirs are likely to consist mainly of low-permeability sandstones. Clean, thickly amalgamated, porous sandstones have not been observed in logs or core and are scarce in outcrop.

Reduced Temperature Gradients in the Foothills

Temperatures and thermal gradients in Brookian and Beaufortian rocks are lower in wells in the foothills than in wells in the coastal plain and along the coast. This thermal setting differs from many overpressured sequences, where temperatures and temperature gradients are high, not low. These lower gradients have been attributed by Deming and others (1992) to a topographically-driven groundwater flow system. These lower temperatures appear to persist to depths where gas reservoirs are likely to be. For a given reservoir pressure, gas density will be greater in a low-temperature reservoir than in a high-temperature reservoir, resulting in somewhat higher recoverable gas reserves.

Uplift and Erosion

The row of numbers below give the approximate amount of uplift and erosion, in feet, from analysis of sonic logs (Burns and others, in press) along the geologic section from the Tulugak well to the Kookpuk well. These values are consistent with O'Sullivan's (1999) estimate of 6,900 feet of uplift in the Seabee well from apatite fission-track data. Formation depths in the foothills have been substantially greater in the past than at present. For example, the top of Kingak Shale in the Seabee well, presently at 13,000 feet, has been buried to a maximum depth of 20,000 feet according to these estimates of burial and erosion, leaving vitrinite reflectance signatures that are well into the gas window. Thus, high levels of thermal maturity have been reached in Beaufortian and Brookian formations despite the lesser thermal gradients present in the foothills.

Logs and Tests from the Tulugak Well

Although relatively few wells have penetrated the Beaufortian and Brookian megasequences in the deeper part of the Colville Basin, inspection of logs and other well data reveal the presence of undercompacted and(or) overpressured intervals in the lower parts of both megasequences. In the Tulugak well, which penetrates the Brookian section, a transition from high to low sonic transit time and an increase from low to high resistivity with decreasing depth suggest that the top of an overpressured interval lies at a depth of about 10,500 ft. However, higher than normal pressure was also encountered in the sand-shale sequence above this depth, as evidenced by the drill-stem test and increase in mud weight to more than 12 ppg at 9,000 ft. In this particular well, the three tested intervals at 16,000, 9,000, and 8,000 ft all produced gas to surface on the first test, but subsequent tests at the same depths showed declines in gas rates and pressures (for example, 0.48, 0.43, 0.35 psi/ft at 8,300 ft), indicating either poor reservoir quality or limited reservoir volumes.

Favorable conditions for gas generation in the lower part of the Torok Formation are evidenced by (1) intermittent gas shows, (2) a vitrinite reflectance trend that exceeds 1.0 percent at 8,000 ft and 2.0 percent at 14,000 ft, and (3) total organic carbon values of 1.5 weight percent from 11,000 to 14,000 ft depth in the Tulugak well. Similar, if not more favorable, conditions for gas generation exist in the Hue Shale, a condensed section and oil-prone source rock interval at the base of the Brookian megasequence and only partially penetrated by the Tulugak well.