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Sandstone and Shale Compaction Curves Derived from Sonic and Gamma Ray Logs in Offshore Wells, North Slope, Alaska - Parameters for Basin Modeling

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INTRODUCTION

Representative compaction curves for the principle lithologies are essential input for reliable models of basin history. Compaction curves influence estimates of maximum burial and erosion. Different compaction curves may produce significantly different thermal histories. Default compaction curves provided by basin modeling packages may or may not be a good proxy for the compaction properties in a given area. Compaction curves in the published literature span a wide range, even within one lithology, e.g., sandstone (see Panel 3).

An abundance of geophysical well data for the North Slope, from both government and private sources, provides us with an unusually good opportunity to develop compaction curves for the Cretaceous-Tertiary Brookian sandstones, siltstones, and shales. We examined the sonic and gamma ray logs from 19 offshore wells (see map), where significant erosion is least likely to have occurred. Our data are primarily from the Cretaceous-Tertiary Brookian sequence and are less complete for older sequences.

For each well, the fraction of shale (Vsh) at a given depth was estimated from the gamma ray log, and porosity was computed from sonic travel time. By compositing porosities for the near-pure sand (Vsh<1%) and shale (Vsh>99%) from many individual wells we obtained data over sufficient depth intervals to define sandstone and shale 'master' compaction curves. A siltstone curve was defined using the sonic-derived porosities for Vsh values of 50%. These compaction curves generally match most of the sonic porosities with an error of 5% or less.

Onshore, the curves are used to estimate the depth of maximum burial at the end of Brookian sedimentation. The depth of sonic-derived porosity profiles is adjusted to give the best match with the 'master' compaction curves. The amount of the depth adjustment is the erosion estimate. Using our compaction curves, erosion estimates on the North Slope range from zero in much of the offshore, to as much as 1500 ft along the coast, and to more than 10,000 ft in the foothills (Panel 3).

Compaction curves provide an alternative to vitrinite reflectance for estimating erosion. Vitrinite reflectance data are often very sparse in contrast to well log data and are subject to inconsistencies when measurements are made by different labs. The phenomenon of 'recycling' can also make the reflectance values of dispersed vitrinite problematic for quantifying erosion. Recycling is suspected in dispersed vitrinite in North Slope rocks, particularly in the younger, Cretaceous-Tertiary section.

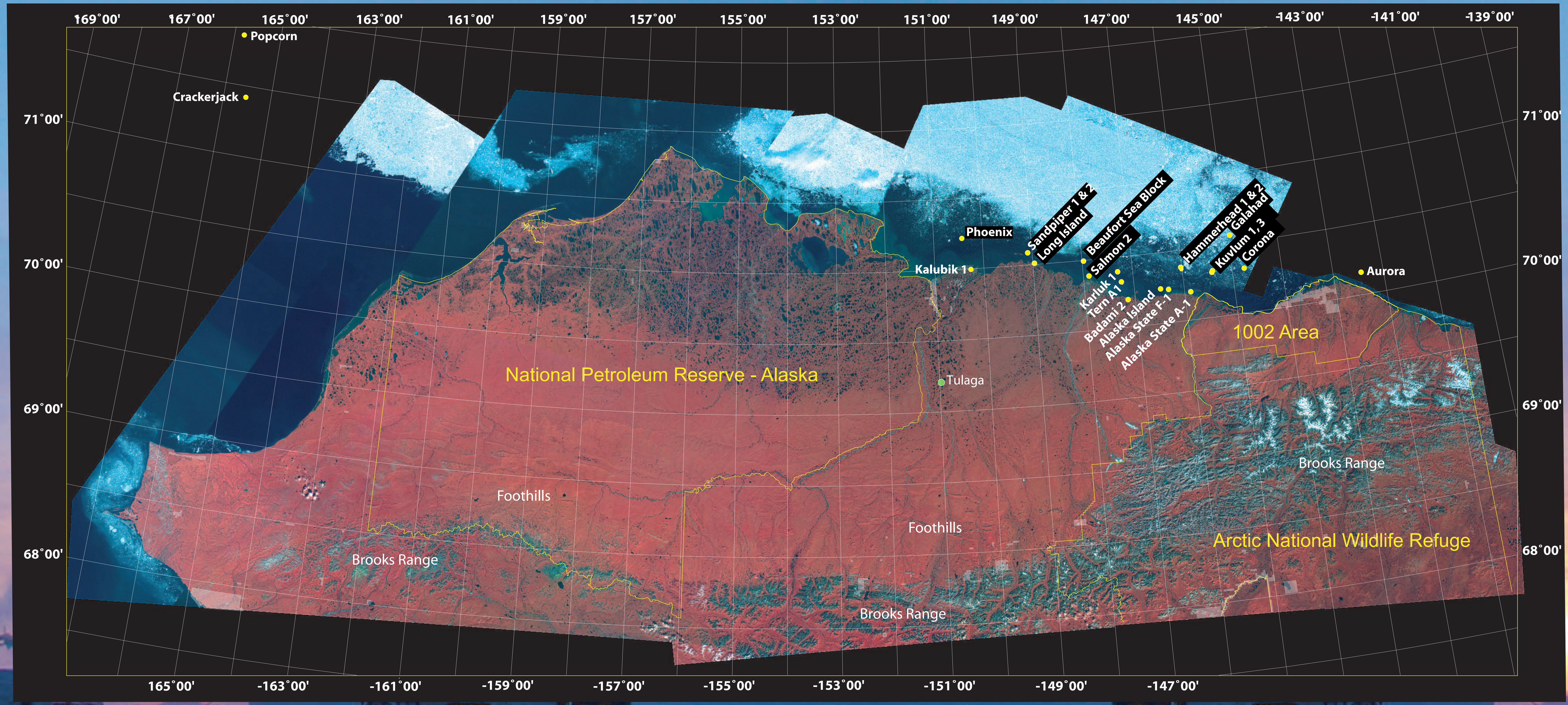
The compaction curves defined here are being integrated into our burial history and thermal models to determine the timing of source rock maturation. An example in Panel 3 shows the results of calculating the maturity of the Shublik Fm. at the Tulaga well using two different sets of shale and siltstone compaction curves. Finally, accurate compaction curves improve a model's ability to realistically simulate the pressure regime during burial, including overpressures.

COMPACTION CURVES, THERMAL GRADIENTS, AND THERMAL MATURITY

The rock's porosity or water content exerts a primary control on the thermal conductivity of the bulk rock. Thermal conductivity together with heat flow determines the thermal gradient. The thermal conductivities of many sandstones and shales fall in the range of 2-3 (W/m˚C); in contrast, water's thermal conductivity is much lower, 0.6 (W/m˚C). The more porous the rock, the lower its bulk thermal conductivity, i.e., the better thermal insulation it provides.

Compaction curves describe the rate of porosity and water loss during burial. Bulk rock thermal conductivities show a corresponding increase with burial. For a given heat flow, the equilibrium thermal gradient increases as conductivity decreases: $Q=\lambda\,(\Delta T/\Delta Z)$ (where Q=heat flow, λ=thermal conductivity, T=temperature and Z=depth)

Compaction exterts an important control on thermal gradients, particularly at shallower burial depths where porosity loss is most rapid. Compaction therefore also influences the degree and timing of source rock maturation.



Map showing the North Slope of Alaska, the Brooks Range, the foothills, and the boundaries of the NPRA and ANWR. Porosity-depth (compaction) profiles were examined in more than 30 offshore wells. Of these, 19 wells (shown as yellow dots) did not appear to have had significant surface erosion. These wells were used to define the sand, silt, and shale compaction curves (Panel 2).

The Tulaga well (green dot) was used to illustrate the effect of compaction curves on thermal maturity calculations (Panel 3).

METHODS

Our study expands on work by Issler (1992) who used sonic transit time (Δt) logs to determine porosities and to characterize compaction properties of mudstones in the MacKenzie Delta, Canada. We use the same approach to determine porosity, but additionally use gamma ray logs to determine a sand/shale ratio for each sonic transit time measurement.

Gamma Ray Index (GI) and Shale Fraction (Vsh)

Shale fraction (Vsh) is used with sonic transit time (Δt) to calculate porosity. The shale fraction is assumed to be approximately equal to the Gamma Ray Index (GI):

$$GI = (GR-GR_{min})/(GR_{max}-GR_{min}) \sim Vsh$$

where GR = an individual, log-derived gamma ray measurement

This approximation, GI ~ Vsh, is appropriate here because we lack the information to calibrate the power laws that relate GI and Vsh for specified degrees of compaction (Asquith, 1982). In addition, we intend to use Vsh in porosity calculations across the NPRA, an area that includes sandstones and shales of widely varying degrees of compaction. The Gamma Ray Index (GI) provides an internally consistent method representing shale fraction over a large geographic area.

Porosity Calculation

Porosity (φ) was calculated from measured sonic transit time (Δt) and shale fraction (Vsh) as follows using the relationship developed by Raiga-Clemenceau (1988):

$$\phi = 1 - (\Delta t_{matrix}/\Delta t)^{1/x}$$

where $\Delta t_{matrix} = \Delta t_{sand}(1\text{-}Vsh) + \Delta t_{shale}(Vsh)$;

$\Delta t_{sand} = 52$ μsec/ft, $\Delta t_{shale} = 67$ μsec/ft; x(shale) = 2.19, x(sand) = 2.05

The matrix travel times Δt and the formation factors (x) were derived from sonic log data for North Slope wells and lab measurements of porosity (see next panel).