Prudhoe Bay and the Alpine Oilfield in northeast Alaska: Geology and Economy

Eva Dolewski

1 Silberhofstraße 1a, 09599 Freiberg

Abstract. In the northeast of Alaska within the North Slope lies the Prudhoe Bay Oilfield and the Alpine Oilfield. The Permian till Middle Jurassic Sadlerochit Group, sediments of the Ellesmerian Formation, form the Prudhoe Bay reservoir strata which were supplied mainly by the source rocks of the Shublik Formation (MASTERSON, 2001). The Alpine Oilfield reservoir is located in the Beaufortian Sequence derived from the surrounding Kingak Shale (MASTERSON, 2001; HANNON et al., 2000). To describe the quality of the source rocks a plot of Rock-Eval pyrolysis $S_2$ versus TOC (wt.%) (K. E. PETERS, et al., 2006) were used.

The Prudhoe Bay Field is the largest oilfield of the USA and provides the main part of the North Slope oil production. The smaller Alpine Oilfield is producing since 2000 and has an estimated reservoir of 429 million barrels recoverable oil.

Introduction

In the north of Alaska just west of the Arctic National Wildlife Refuge (ANWR) and east of the National Petroleum Reserve- Alaska (NPRA) lies the 59,500 km² North Slope (Fig.1). It contains the Prudhoe Bay and the Alpine Oilfield, two of the most important oilfields in Alaska.
Smith (1987) add this area to be parcel of the North Alaska microplate which is on its part a section of the larger Arctic Alaska microplate.

The North of Alaska is part of the of the Arctic Alaska microplate, a small continental fragment (Hubbard et al., 1987). During early cretaceous time the opening of the Canadian basin resulted in a rotating of northern Alaska counter clockwise away from Canada (Fig.2; CARY, 1958; TAILLEUR, 1973; GRANTZ and others, 1998).

Evolution of North Slope Geology

The stratigraphic of the North Slope can be divided in four sequences: (from oldest to youngest)

- Franklinian Sequence
- Ellesmerian Sequence,
- Beaufortian/Rift Sequence
- Brookian Sequence

The Franklinian Sequence a stable continental platform in the Pre-Mississippian builds the basement of the North Slope Stratigraphic. It consists of fractured carbonate, argillite, quartzite, volcanic and granitic rocks that were deformed, uplifted and eroded during Cambrian through Devonian.
The eroded material of the uplifted Franklinian high provided the northerly source of sediments for the **Ellesmerian Sequence** (Fig.3, A). Its sediments (marine carbonates, marine and nonmarine clastic rocks) were deposited during the Mississippian through early Jurassic time in a terrain of a subsiding foldbelt (HUBBARD, 1987).

During Jurassic time two major tectonic events occurred that affect the geology of the North Slope (Fig.3, B). First of all the rifting of the northern part of the Artic Platform in early Jurassic (GRANTZ and MAY, 1983), with the result, that the source for the Ellesmerian sedimentation from the north became less and until it completely stopped. The second event is described by Box and Patton (1987) as an uplift and deformation in the region of the present central southern Brooks Range in the late Jurassic time. This was an effect of the initial stages of subduction of the North America plate beneath the intraoceanic Koyukuk arc. However the rifting in the north caused a faulting and uplift of the Franklinian and the Ellesmerian Sequence and created a normal fault blocks, consisting of horst and graben, which were filled.
with the sediments of Ellesmerian and Franklinian, forming the **Beaufortian Rift Sequence** (CRAIG, et al., 1985) containing marine shales, siltstones and sandstones.

The Barrow Arch, the Hinge Line and the Colville Basin were formed during the rifting and onset of the Brookian Orogen on the southern Arctic Platform. According to Grantz and May (1983) the Hinge Line marks the point at which the northward slope of the basement surface increases markedly into the Canada Basin.

The Barrow Arch is a structural high, created during the Jurassic and Cretaceous and is characterized by a passive-margin subsidence of the Arctic Platform in the middle Cretaceous which constitutes the northern flank. The southerly dipping Arctic Platform forms the south flank of the arch.

The loading of north vergent, late Jurassic and Cretaceous sediments and nappes of the ancestral Brook Range tilted the platform southwards and created the Colville foreland basin.

Since the Late Cretaceous through the Paleocene time the eroded clastic sediments of the Brook Range filled the Colville Trough, eventually overstepping the Barrow Arch by middle Albian (Fig.3, C) (GRANTZ and MAY, 1983)

**Source rocks and reservoir properties of Prudhoe Bay and Alpine**

Prudhoe Bay and the Alpine Oilfield are a result of combination of structural and stratigraphic circumstances (Fig. 4). They were formed by unconformities, which are erosional surfaces in the rocks, formed when the rocks were uplifted during the rifting and subsequently buried again.

For example, the Prudhoe Bay field is sealed by a normal fault in the north and by south-dipping shales in the south, which overlie the reservoir sand. The western extent of the oil is limited by a structural saddle in the upper surface of the reservoir. Unconformities and overlying shales seal the crest and eastern flank of the oilfield (JAMES D. CRAIG; KIRK W. SHERWOOD; PETER P. JOHNSON, 1984)
Within the Ellesmerian Sequence lies the Sadlerochit Group (Fig.5) which implies the Ivishak Formation. This formation is composed of sand and conglomerates and represents the principal oil-bearing reservoir of Prudhoe Bay. The excellent reservoir quality of the Sadlerochit Group is caused by two main environments of deposition. The lower Sadlerochit was deposited in a shallow-marine environment, and the upper part in a nonmarine alluvial complex (Fig.6). Claystone and shales shape the base of the Sadlerochit Group and grade upwards into interbedded, fine-grained sandstones and
shales. In large part the upper section contain of the recoverable hydrocarbons at Prudhoe Bay field and is made up of fluvial interbedded sands and clays graining upward into braided-stream sands and conglomerates. The porosity of the field is limited by silica cement, generally as overgrowth on quartz grains and one of the most important diagenetic factors.

The Prudhoe Bay area mainly contains crude oil from the middle to upper Triassic Shublik Formation, approximately 59% (MASTERSON, 2001). Additionally, oil from the Hue Shale and the Kingak Shale were added to create a mixture of oil types in the Prudhoe Bay field (Bird, 1994). The Shublik Formation is a heterogeneous source rock composed of marin carbonate, marl, shale and phosphorite facies. Robinson et al. (1996) distinguishes this formation into two subsequences. The lower part is dominated by laminated marls and shales that contain oil-prone organic matter consisting of mixtures of fluorescent amorphous kerogen, marine alginate, and other exinites deposited under suboxid to anoxid conditions. The upper part represents a regressive milieu which contains bioturbated shale. Due to the fact that the upper part is deposited under more toxic conditions and is also more bioturbated, the shale contains mainly gas-prone or inert organic matter.

In a study of Shublik rock samples from a six-well profile, Bird (1994) acquired a mean value of total organic carbon (TOC) of 2.3 wt.%, with a range of 0.49-6.73 wt.% and a thickness between 24-149m (max.180 m).

The Alpine reservoir can be stratigraphically classified between the Permian-Triassic Prudhoe Bay and the lower Cretaceous Kuparuk River fields within the Beaufortian strata (Fig.5). The Alpine sandstone is the youngest upper Jurassic sand within the Kingak Shale and has been subdivided into two units, A and C (Fig.7). Alpine A comprises an upward-coarsening shoreface of very thin-bedded, very fine to fine grained, well-sorted sandstone to muddy siltstone. It represents a southward-prograding wave-dominated deltaic and shoreface system deposited along a south-facing passive continental margin during a highstand of sea level. The sandstones have a thickness of 0-6 m, with an average porosity of 17% and an average permeability of 5 miliardcys.

The overlying Alpine C sandstones are transgressive nearshore deposits and are composed of highly bioturbated, very fine- to medium-grained quartz sandstones.

Hannon et al. (2000) characterises the base of Alpine C as a lowstand unconformity, modified by transgressive ravinement, and erodes locally into the Alpine A unit, whereby its thickness increases. On this
account, much of the Alpine A unit is missing. Typically, Alpine C sandstones have a thickness of 1.5-33 m, an average porosity of 20% and an average permeability of 15 milidarcys. Most of the reserves occur in the Alpine C sequence, although the reservoir qualities and thickness vary field wide. The Alpine field is thought to be the largest accumulation of oil derived mainly from Kingak source rock (HANNON et al., 2000; MASTERS, 2001). The Kingak Shale contains a mixture of Jurassic marine and terrigenous organic matter in a marine siliciclastic setting that was influenced by tectonic rifting (MAGOON and CLAYPOOL, 1984; HUBBARD et al., 1987).

Furthermore, Houseknecht and Bird (2004) define four sets of strata within the Kingak Shale (K1-K4). However, only the base of K1, which confines the contact between the Kingak Shale and the underlying Triassic strata of the Sag River Sandstone and the Shublik Formation, respectively, is the most organic-rich interval. For example, the lowermost 14.9 m of the Kingak Shale has an average of 5 wt.% TOC (MASTERS, 2001).


Figure 8 shows a plot of Rock-Eval pyrolysis S2 versus TOC (wt.%). This kind of plot is very useful to compare the petroleum-generative potential of source rocks. The axis of abscissa represents hydrocarbons (HC) that can be generated by pyrolytic degradation of organic matter in rock samples (mg HC/g rock; Peters, 1986). The ordinate stands for the concentration of “total organic matter” in wt.%. The slopes of the
lines correspond with the hydrogen index \(100 \times \frac{S_2}{\text{TOC}, \text{mg HC/g TOC}}\).

Peter and Cassa (1994) classify four organic matter types:

<table>
<thead>
<tr>
<th>Type</th>
<th>Generative potential</th>
<th>Hydrogen index (mg HC/g TOC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>very oil-prone</td>
<td>&gt; 600</td>
</tr>
<tr>
<td>II</td>
<td>oil-prone</td>
<td>300-600</td>
</tr>
<tr>
<td>II/III</td>
<td>oil- and gas-prone</td>
<td>200-300</td>
</tr>
<tr>
<td>III</td>
<td>gas-prone</td>
<td>50-200</td>
</tr>
<tr>
<td>IV</td>
<td>inert</td>
<td>&gt; 50</td>
</tr>
</tbody>
</table>

**Tab.1:** The table shows the classification of the source rock qualities after Peter and Cassa (1994)

Additionally, the quantities of organic matter can be categorized as poor, fair, good, very good and excellent depending on the value of total organic matter: < 0.5, 0.5-1, 1-2, 2-4 and >4 wt.% TOC.

To make sure that neither the TOC nor \(S_2\) is significantly reduced by prior petroleum- generation only data from thermally immature or early immature samples were used for the analysis. Furthermore, only wells with significant numbers of Rock- Eval and TOC data are included on the plot.

If you compare the quantity (TOC and Rock-Eval pyrolysis \(S_2\)) and quality (hydrogen index) of organic matter of the four sampled source rocks, it is obviously that the Shublik Formation (the main Prudhoe Bay source rock) exceeds the other three source rocks. Many samples from the Shublik Formation contain more TOC (> 4wt.%) than the others, and most of these organic rich samples are composed of very oil prone type I or oil prone type II organic matter (hydrogen index >600 or 300- 600 mg HC/g TOC, respectively). Samples representing the other three source rocks (containing the Alpine source rock Kingak Shale) have less petroleum- generation potential, because of their generally lower TOC and hydrogen index, but most of them still contain significant amounts of oil prone type II or oil- and gas prone type II/III organic matter. The samples from the pebble shale have two different trends which indicate two principal groups that contain either oil- prone type II or inert type IV organic matter.
Economy of Prudhoe Bay and Alpine Oil Field

Alaskan crude oil

In 2005, Alaska crude oil represented 17% of total U.S. crude oil production and 6% of all crude oil processed in the United States (7.61 million bbl/day).

After Texas (according to the “Energy Information Administration” 4,613 million barrels oil proved reserves), Alaska ranks second among the States in crude oil reserves (rang 3rd including Federal Offshore). For example, on December 31st, 2004, Alaska’s proved reserves were amount to a total of 4,327 million barrels. However, the crude oil production in Alaska has declined from his peak 1988 of just over 2 million barrels per day to 864 thousand barrels per day in 2005.

Prudhoe Bay

Prudhoe Bay has an estimated reserve of 25 billion barrels. But only 13 billion barrels are classified as recoverable and approximately 77 percent (10 billion barrels) have already been produced, which is roughly 10 years of production at the current rate. 1988, the Prudhoe Bay Field produced 1.6 million barrels per day. 17 years later the production dropped down on an average of 370 thousand barrels per day. However Prudhoe Bay still provides the main part of the North Slope oil production (October 2006: 9,580,189 barrels).

1968 the Prudhoe Bay Oilfield was discovered by “BP Exploration (Alaska) Inc.”. Although BP is the operator, its only owns 26.36%. Other shareholders are “ExxonMobile AK Production, Inc.” (36.39%), “ConocoPhillips Alaska, Inc.” (36.07%), “Chevron U.S.A, Inc.” (1.16%) and “Forest Oil Corporation” (0.02%).

Alpine Oilfield

The Alpine Oilfield was found 1994 and declared commercial in 1996. Since 14th of November 2000, they started to produce crude oil. It has an estimated reserve of 1 billion barrels, whereas just 429 million barrels are recoverable. Thus, it is one of the largest onshore oil discoveries in the last decade. In 2005 they were producing 115,000 barrels per day, but in 2006 two new satellite fields were started up (Fiord on the 9th of August and Nanuq on the 26th of November ) the production is going to rise. Nanuq is expected to have
peak production of approximately 15,000 barrels of oil per day and Fiord approximately 22,500 barrels of oil per day in 2008. Compared to the Prudhoe Bay oilfield the Alpine Field has only two shareholders. “ConocoPhillips Alaska, Inc” conducts 78% of the oilfield and the “Anadarko Petroleum Cooperation” 22%.

Conclusion

The Prudhoe Oilfield is able to produce crude oil for the next 10 years. Therefore it is necessary to explore new resources to make sure that the full supply of crude oil will be guaranteed. One example is the new Alpine Oilfield which started production in 2000. The Rock-Eval pyrolysis $S_2$ versus TOC plot shows that the quality of the Kingak Shale is nearly as good as the quality of the Shublik Formation, the source rock of Prudhoe Bay. However the recoverable resources of the Alpine Oilfield covers only a small part of the recent production of the Prudhoe Oilfield. On this account, it will be the duty of geo scientist in the future to find more economic significant deposits.

References


Sharman, G.D., June 30, 1993: Characterization of oil and gas reservoir Heterogeneity. Petroleum Development Laboratory, University of Alaska, Fairbanks


Burns, B. A., et al. (2003): The Late Jurassic Alpine C Sandstone- A bioturbated, paralic reservoir deposited during a slow transgression: North Slope, Alaska. AAPG Convention, Salt Lake City, Utah


www.columbia.edu/~sp2023/scienceandsociety/web-pages/Prudhoe%20Bay.html

www.eia.doe.gov/oil_gas/petroleum/info_glance/petroleum.html

http://Alaska.bp.com

www.dmtcalaska.org