INSIGHTS FROM FLUID INCLUSIONS ON THE PETROLEUM SYSTEMS OF THE BARENTS SEA

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Introduction

The Barents Sea, historically a high-risk exploration province because of uncertainty surrounding petroleum system elements, has recently experienced a number of successes, including discovery of significant liquids reserves (e.g., the Johan Castberg complex and satellite discoveries) and extension of viable discoveries to the Cretaceous and Paleozoic section. Early perceptions were that the area was prone to gas and small residual oil columns and that Tertiary exhumation had potentially breached, redistributed, or dissipated the contents of early traps. The efficacy of seals for shallow targets was in question.

We present results of analysis of fluid inclusion studies from 2005 to the present, involving 72 exploration wells and 36 shallow boreholes. This retrospective allows comparisons to subsequent exploration results, some of which clearly support inferences made from nearby wells before the discoveries were made. The purpose is to demonstrate the value of fluid inclusion analysis performed early in the exploration cycle to clarify basic petroleum system controls, optimize exploration efforts, and predict eventual drilling results.

Results

Bacterial microseeps, produced by bacterial sulfate reduction coupled to oxidation of light, thermogenic hydrocarbons moving nearly vertically from depth, are identified in area wells with fluid inclusion stratigraphy (FIS) data. However, here they are not as strongly developed as in the Norwegian Sea, perhaps due to deep-burial sterilization. FIS analysis microseeps are statistically correlated with deeper liquid petroleum accumulations worldwide. However, weak or nonexistent bacterial microseeps in the Barents Sea, which has experienced at least 500–1500 m of uplift, is not compelling evidence for lack of deeper charge.

Deep, thermal alteration and evidence of in situ secondary cracking of oil to gas has been identified in intervals that are either currently deeply buried or are inferred to have had high paleo-temperature. This is generally documented at fluid inclusion paleo-temperatures greater than 140^{o}C, consistent with previous estimates of the temperature threshold for thermochemical sulfate reduction. Strongest evidence occurs in Permian strata, which are dominated by carbonates with sulfate-rich, highly saline aqueous fluid inclusions. Some occurrences clearly represent paleo-columns of oil, which appear to have been subsequently buried and converted to gas and pyrobitumen in place. This oil was likely derived from a Permian or older source rock, and contributions from the Permian have been recognized in biomarker data from shallower reservoirs. Additionally, the secondary gas has migrated into the Jurassic and Triassic section, creating or contributing to a separate gas phase.

Significant paleo-columns of oil are documented in Cretaceous, Jurassic, and Upper Triassic sandstones; Jurassic occurrences are the most common. Rarely, paleo-columns of Permian-sourced oil are documented in the Permian strata that have not been as deeply buried. Paleo-columns up to 300 m thick are recorded in the Jurassic section, with fluid inclusion oil that ranges from 25 to 45 degrees API gravity. In some cases, paleo-columns of earlier, less mature oil are recorded within reservoirs that currently contain higher gravity oil or gas-condensate. This suggests displacement or loss of the early phase and provides additional exploration avenues for these areas. In other cases, measured fluid characteristics (gravity and phase) are consistent with present-day charge.

The Hekkingen formation appears to have remained an effective regional top seal to Jurassic reservoirs after oil charging, despite uplift. Evidence, on the basis of fluid inclusion data, of breached seals in this stratigraphic section is rare. This contrasts with the commonly held belief that uplift resulted in exsolution of gas and subsequent seal failure. In fact, microthermometric data suggests that both oil and gas were present in at least some of these reservoirs at near-maximum burial. Some of that gas appears (e.g., isotopically) to be dissociated from the in situ oil and is likely derived from a deeper source via either secondary cracking of early oil or generation from a gas-mature source rock. Rarely, paleo-accumulations in the Cretaceous formations may represent remobilized oil from breached Jurassic sequences. Deeper reservoirs (e.g., Triassic) appear to show evidence of vertical gas migration; hence, possible seal failure in some instances. This might be expected if voluminous gas generation from gas-mature source rocks and secondary cracking of oil to gas generated high overpressures in these intervals while the section was near maximum burial depth and temperature. Microthermometry data suggest that oil charging occurred near maximum burial temperature in many cases, and often imply uplift of 500–1500 m, consistent with independent estimates.

"Proximity-to-pay" anomalies, defined by anomalous concentrations of organic acid and/or benzene in FIS data, are very common in the main Jurassic reservoirs, both where paleo-accumulations are indicated, and where migration without accumulation has apparently occurred. In general, these features indicate retained accumulations within an 8-km radius. The extensive distribution of these anomalies suggests that the Jurassic and Upper Triassic sections remain prime exploration targets and that oil originally present in many paleo-accumulations has not been lost but, more likely, has been redistributed to adjacent structures.

An example from the Johan Castberg area (discovered in 2011) illustrates the potential value of early-stage fluid inclusion data. Fluid inclusion data from a nearby dry hole (drilled in 1988; fluid inclusions analysed in 2005) accurately predicted that Hekkingen-sourced oil and a separate, deeper-sourced gas phase was reservoired in Jurassic reservoirs nearby and that the displaced oil likely ranged from 34 to 36 degrees API gravity. Data also correctly suggested that nearby accumulations may exhibit wax precipitation problems and provided estimated wax-appearance temperatures. The volume of oil originally present could be calculated, and the timing of filling and spilling events could be approximated. Finally, tight wet gas accumulations are implied to be present in the deep Snadd Formation in the region, although these have not been penetrated to date.

Conclusions

Application of fluid inclusion techniques to exploration wells in the Barents Sea has unveiled a more complete understanding of processes that have led to the current distribution of recoverable hydrocarbons. These methods provide fundamental and practical information for exploration and field development and can be used effectively at an early stage to help understand complex systems.