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Development of Petroleum Systems in Northern Alaska – Timing of Petroleum System Events Controls Presence of Accumulations

Introduction

The Alaska North Slope, including the adjacent Beaufort and Chukchi continental shelves, is one of the remaining petroleum exploration frontiers, and is estimated to contain most of the undiscovered oil and gas resources in the North American Circum-Arctic (Gautier et al., 2009). We present a calibrated 3D model of the Alaska North Slope region that reconstructs, quantifies, and evaluates the development of the individual petroleum systems, burial history, and thermal evolution, as well as migration, accumulation, and preservation of hydrocarbons.

The geologically complex Northern Alaska petroleum province evolved through the tectonic stages of passive margin, rift, foreland basin, and foreland fold and thrust belt. Petroleum was generated from several source rock units, and many reservoirs show evidence of mixing of hydrocarbon source types. Rift-related structures and a regional, break-up unconformity (LCU – Lower Cretaceous Unconformity) are critical trapping and migration components of the largest oil and gas accumulations. In addition, stratigraphic traps that developed during extensional and compressional tectonic regimes show significant resource potential in Jurassic through Cenozoic shelf and turbidite sequences.

The Model

Regional modeling of the tectonic and sedimentologic evolution of Northern Alaska through time provides an opportunity to integrate and analyze many aspects of petroleum system development.

The model encompasses 275,000 km² (832 × 520 km with a grid spacing of 1 km; Figure 1) and includes the Chukchi platform, the Beaufort continental shelf, and the foothills of the Brooks Range. The model is based on >48,000 km of newly interpreted 2D seismic and a database of >400 wells that include calibration and geochemical data. Particular attention was paid to mapping onlap and truncation relations developed during passive margin and rifting stages (Mississippian to Early Cretaceous) in recognition of their importance as hydrocarbon migration pathways and traps.

The overlying foreland basin sediments reach a total thickness of up to 8,000 m and were deposited during Late Cretaceous and Cenozoic time predominantly from WSW to ENE as a prograding sequence (Bird, 2001). The reconstruction of this paleo-geometry—diachronous deposition, facies variation, and thickness distribution as well as variations in paleo-basin geometry—was one key element of this study. The designation of depocenters through time had a major impact on the timing of maturity, generation, and migration of hydrocarbons. These time-transgressive deposits were reconstructed by using timelines rather than formations. They were mapped from surface traces and shelf edges. The effects of multiple Tertiary erosion events were also taken into account.

Abundant well data exist for the Alaska North Slope and allow calibration of both pressure and temperature in the subsurface. The pressure was calibrated in two steps: one related to rock compressibility, the other to permeability (overpressure calibration). Heat flow was calibrated against vitrinite reflectance and later cross-checked with corrected bottom-hole temperature data. The assigned heat flow maps, sediment-water interface temperatures, and paleo-water depths are also consistent with regional geology and recent concepts of the thermal regime on the North Slope.

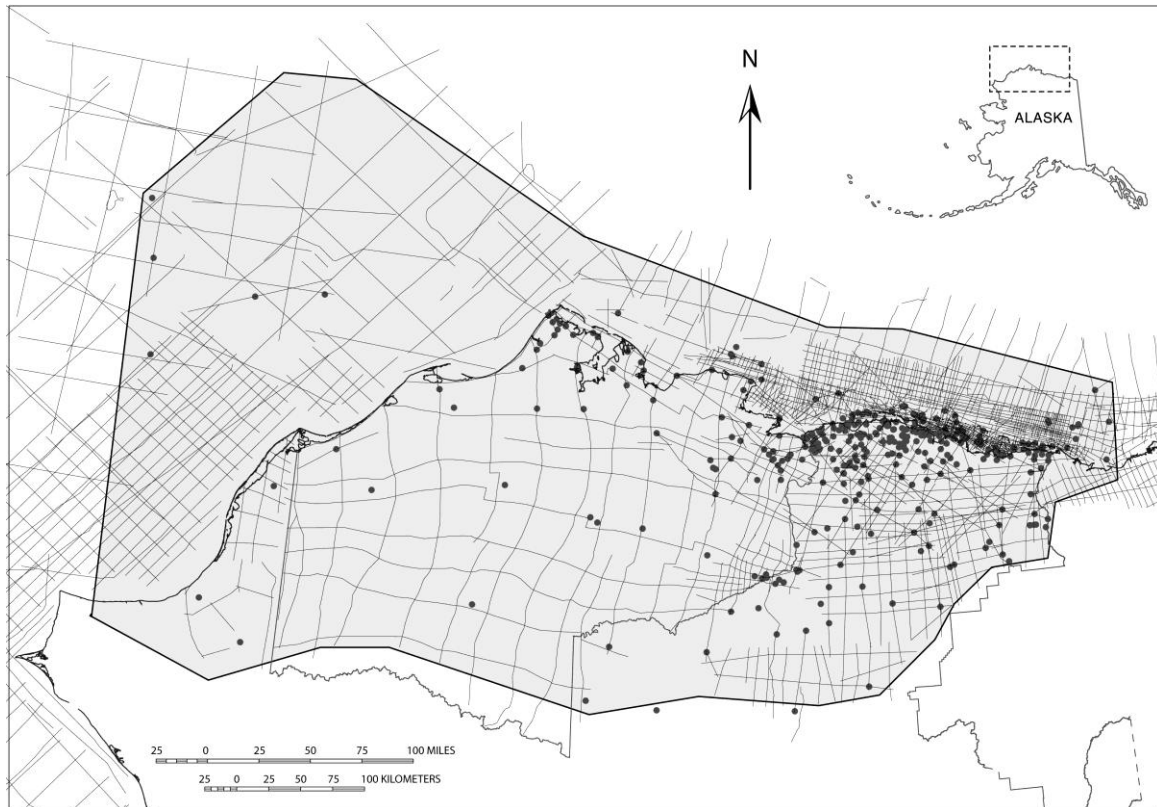


Figure 1: Location of the study area showing the seismic lines and wells used for structure and isopach maps.

Contour maps of original TOC (TOC_o) and HI (HI_o) for source rocks were taken from Peters et al. (2006) and extrapolated to the limits of the present study. Thermally immature source rock samples were analyzed using the new 'Phase Kinetics' procedure developed and calibrated for PVT-controlled prediction of petroleum phases and properties, such as API and GOR (di Primio and Horsfield, 2006). The results of the analyses were assigned to the respective source rocks.

Modeling Results

Forward deterministic computations were applied to simulate the burial history of the rock units and the generation-migration-accumulation of petroleum within a 3D cube through time (e.g., Hantschel and Kauerauf, 2009). A key aspect of the 3D Alaska North Slope model is that it incorporates the time-transgressive deposition of the Cretaceous-Tertiary Brookian Sequence, the thickness difference between the foreland basin axis and the rift shoulder, and the diachronous pulses of Tertiary uplift and erosion (Figure 2).

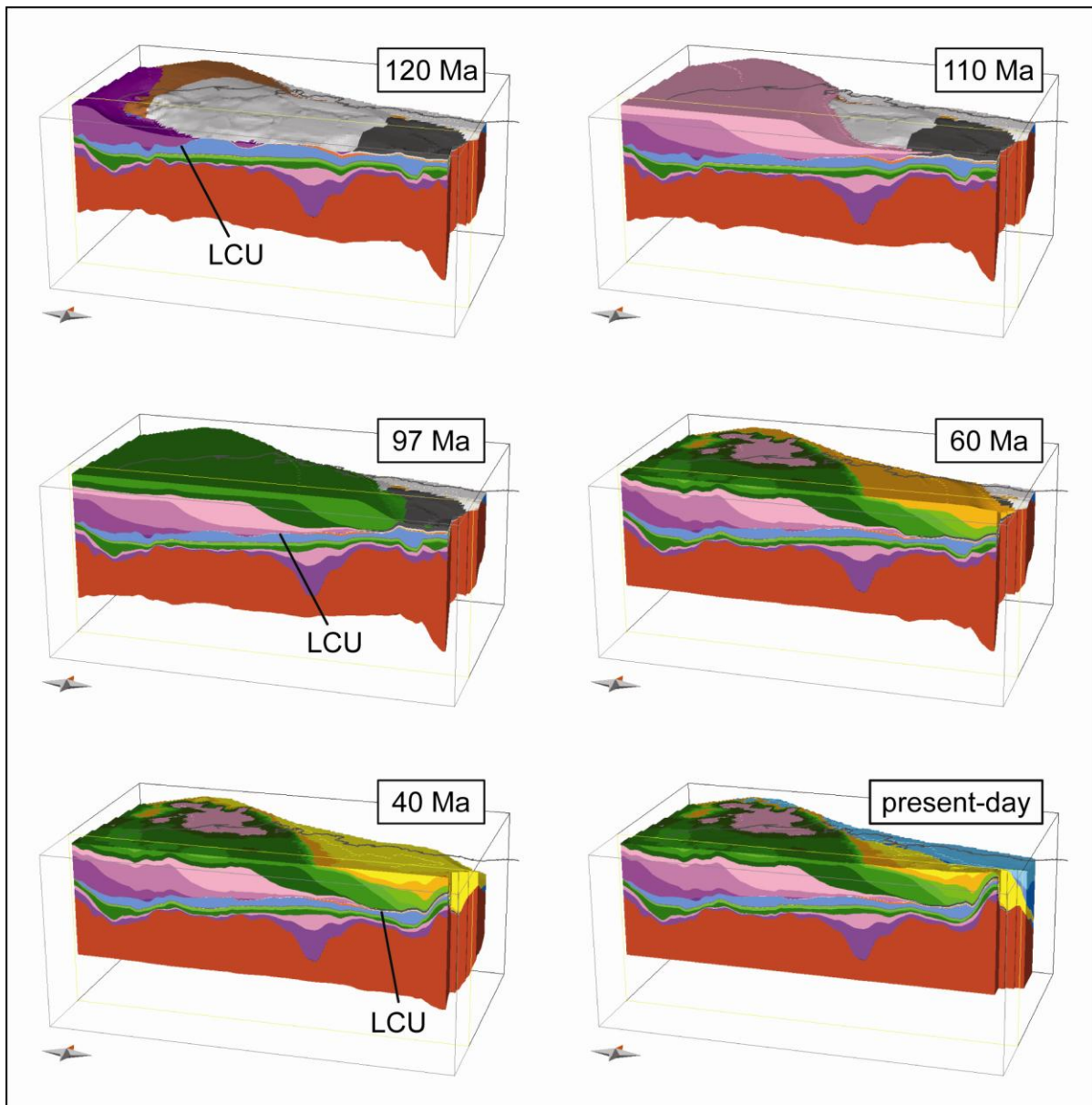


Figure 2: Modeled progradation of the Brookian Sequence across northern Alaska for selected timeslices. Note position of the LCU (Lower Cretaceous Unconformity).

The model indicates that the thermal maturity of Pre-Brookian deposits was dynamic because it was controlled mainly by progradation of the Brookian Sequence. The time-transgressive deposition of the Brookian Sequence in combination with overall basin geometry also controls hydrocarbon generation and the direction of its migration. Most migration pathways were directed toward the north with hydrocarbons accumulating mainly in combination structural-stratigraphic traps along the Barrow Arch.

Simulation results show a general decrease of the relative contribution of the Triassic (Shublik Formation) source rock and an increase of that of the Cretaceous (Hue Shale) source rock along the rift shoulder from west (Point Barrow) to east (Point Thomson) over a distance of ~400 km, and are in agreement with conclusions of Peters et al. (2008) who examined geochemical characteristics of known mixed crude oils using multivariate statistics.

Model results also demonstrate the importance of the relative timing of trap formation and expulsion from the source rock. Petroleum system event charts extracted from the model show how the relative timing of these events impacts risk.

At super-giant Prudhoe Bay accumulation, North America's largest, trap formation here on the rift shoulder preceded expulsion, resulting in a major accumulation. Biomarkers show that Prudhoe Bay oil is a mixture of oils derived from the Triassic Shublik Formation and Cretaceous Hue Shale with lesser input from the Jurassic Kingak Shale (Peters et al., 2008). These results are consistent with the 3D model (Figure 3): the Shublik and Kingak source rocks started to expel hydrocarbons during the Cretaceous mainly in the foreland basin which migrate northward to the rift shoulder. During Tertiary time burial was mainly restricted to the easternmost parts of the foreland basin and the passive margin north of the rift shoulder where associated tilting and subsidence resulted in hydrocarbon generation from the Hue Shale. These hydrocarbons expelled downwards into a zone related to the Lower Cretaceous (break-up) Unconformity (LCU) along which they migrated toward the Barrow Arch and resulted in late-stage contribution of Hue oil in the Prudhoe Bay field.

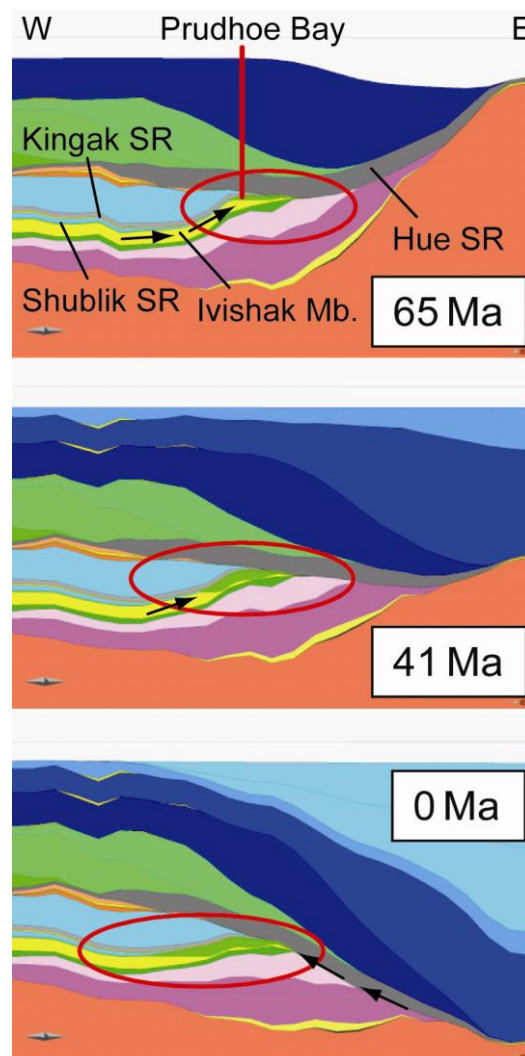


Figure 3: Modeled Cenozoic development of the Prudhoe Bay field along a west-east profile. Contribution of Hue oil is related to eastward-shifted subsidence as result of the prograding Brookian Sequence.

Debate persists over the reasons for failure of the Mukluk wildcat well. At the time of drilling, the Mukluk prospect was estimated to contain 1.5 billion bbl of recoverable oil in a Prudhoe Bay look alike structural-stratigraphic trap, although subsurface imaging was uncertain due to difficulty in assessing seismic velocities through permafrost. Drill cuttings and core data showed extensive oil stain in the target formation. The 3D model shows that initially petroleum accumulated, but later spilled to the southeast through a thin sandstone (Kuparuk C-D) overlying the break-up unconformity toward the Kuparuk River field during Tertiary tilting.

Preliminary 3D simulations predicted a large petroleum accumulation on the west-central part of the rift shoulder in the Barrow Peninsula area, although only a few small gas fields are currently known (S. Barrow, E. Barrow, Sikulik) near the Avak structure, which resulted from a middle-late Turonian meteor impact. Our revised 3D model accounts for the effects of the meteor impact on temperature and permeability of the target rocks. The model predicts a large accumulation prior to impact, but simulated present-day accumulations occur only to the west, south, and east of the Avak structure, in agreement with known accumulations (Figure 4).

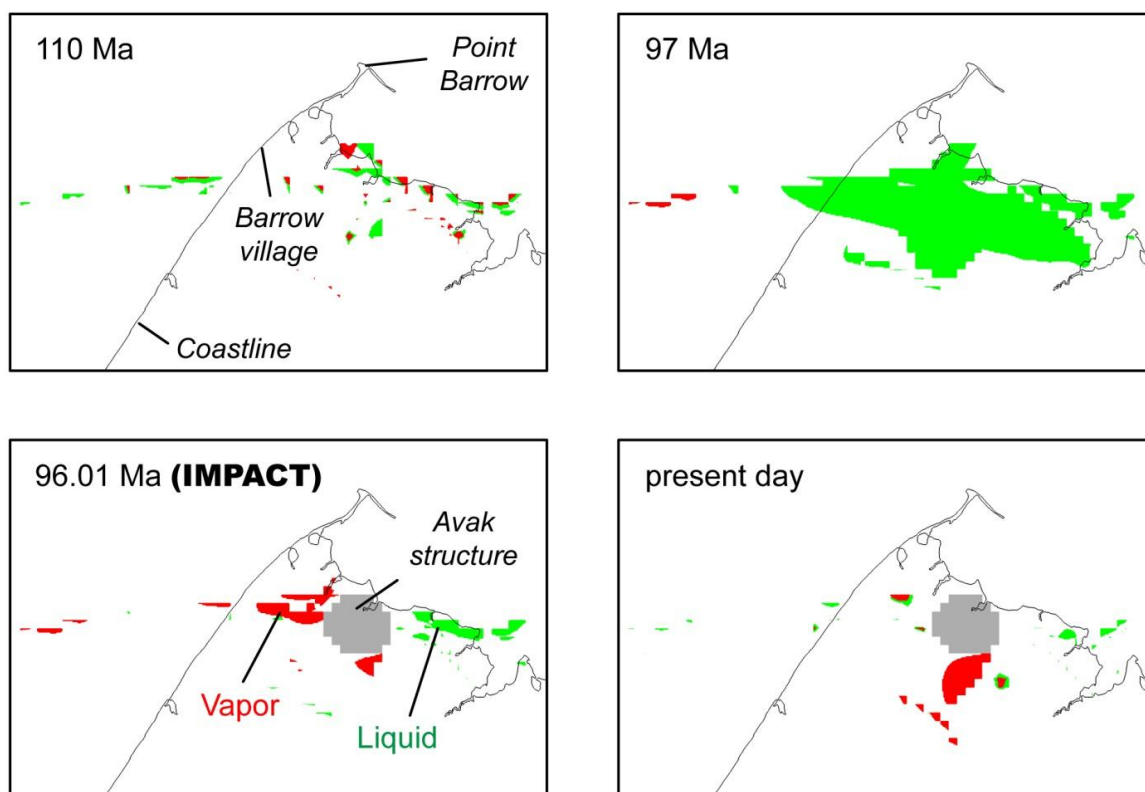


Figure 4: Model results including the Avak meteorite impact. Simulation of hydrocarbon maturation, migration, and accumulation through time on the Barrow Peninsula shows a large accumulation at 97 Ma. At about 96 Ma, the impact occurred, producing a circular, crater-like damage (gray), effectively increasing the permeability and temperature. After the impact, the large liquid accumulation disappeared. At present day, the model shows several vapor accumulation near the impact structure.

Conclusions

The 3D petroleum system modeling study of the Alaska North Slope provides a unique geological framework to help reduce petroleum exploration risk and assess the remaining potential hydrocarbon resources in this remote, but prolific province.

Among the many geologic relations utilized, the model incorporates i) details of passive margin (Ellesmerian) and rift stage (Beaufortian) strata, including onlap and truncation structures and ii) the progradational geometry of foreland basin (Brookian) strata and its impact on the generation, migration, entrapment and loss of hydrocarbons through geological time. The effects of multiple episodes of Cenozoic uplift and erosion events were also taken into account.

The deep burial and diachronous, eastward-shifting depocenters of the foreland basin activated multiple petroleum systems, resulting in an eastward-shift in timing of petroleum generation and modification of the directions of petroleum migration. Model results also point to the importance of relative timing of hydrocarbon generation-migration and trap formation, e.g., whether petroleum is accumulated or lost from the system. This is fundamental for the understanding of the North Alaskan petroleum systems.

This study represents one of the largest regional-scale computer models of a sedimentary basin to date and is unique with respect to complexity and details. It provides excellent opportunities for analysis of both regional and local geologic features using 'local grid refinement' as indicated by the modeling results of the Mukluk failure and the Avak meteorite impact. Finally it provides a training set on how to build a regional model of a very complex sedimentary basin.

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