C-9

THE INTERACTION OF STRUCTURAL STYLE AND PETROLEUM ACCUMULATIONS IN THE BERKINE PORTION OF THE GHADAMES BASIN, ALGERIA

FRANCOIS J. GAUTHIER, LANS TAYLOR and ROBERT J. LUNN
Anadarko Petroleum Corporation, 17001 Northchase Drive, Houston TX 77060, USA

Introduction

The Berkine portion of the Ghadames basin has yielded significant reserves in the last decade. The Great Eastern Erg of Algeria, although having been explored before in the 1970's and 1980's, has become one of the hottest petroleum provinces in the world with recent discoveries totaling well over 3 billion barrels of oil recoverable (figure 1). The Berkine sub-basin is predominantly a Paleozoic pericratonic basin, with the sediment fill being approximately equally partitioned between the Paleozoic and Mesozoic series. Discoveries have been made in both Paleozoic and Mesozoic aged rocks, with the majority of recoverable reserves held in Lower Triassic sands referred to as the TAGI.

Several papers have been published by numerous authors on the Paleozoic and Mesozoic petroleum systems of the Berkine Basin and on the depositional environments and sedimentological character of the reservoir rocks. Additional papers have also been published discussing the overall level of exploration and the estimated remaining reserve potential of this new and prolific oil and gas basin.

Our study focuses on the timing and geometry of faulting and its relationship to hydrocarbon accumulations. Understanding these relationships is a critical aspect of the exploration process that allows us to extrapolate future trends in this basin and draw analogies to other basins in the circum-Mediterranean region.

Berkine Sub-Basin Exploration History

Exploration in the Berkine sub-basin began in the 1960's, but initial efforts were hampered by the topography of the Great Eastern Erg, and early seismic investigations shed little light on the complex patterns of faulting and folding present in the basin (figure 2). As a result, early discoveries were made only along the crests of prominent fault-bounded ridges present on the western flank of the basin. The majority of exploration activity in the central portion of the basin has taken place in the last 15 years, with most discoveries taking place since 1990. The advent of new seismic technology has enabled clearer imaging of the subsurface through the thick cover of sand. The large discoveries of the 1990's are associated with fault trends that roughly parallel the ridges of the earlier discoveries, but which were not imaged on the older vintage seismic data.

With twenty-two new discoveries in both Paleozoic and Mesozoic aged reservoirs, and extensive coverage of both 2D and 3D seismic data, we have an excellent opportunity to characterize the structural evolution of the system and to understand how different fold and fault trends interact to create structural closures. Our analysis offers new insights on what is required to trap hydrocarbons in this highly productive system. This insight may be extended into other north African basins and into new less explored Mediterranean basins.

1. Map of the Ghadames Basin showing discovered oil and gas fields and the major structural trends.

Tectonic Review

The tectonic evolution of the Berkine sub-basin can be subdivided into five phases: (1) the late Proterozoic Pan-African Orogeny, (2) Cambrian through Carboniferous epierogenic subsidence and sedimentation, (3) the Permian Hercynian Orogeny, (4) Triassic and Jurassic extension, subsidence, and sedimentation, and (5) the Cretaceous and Cenozoic Austrian, Pyrenian, and Alpine Orogenies.

The Pan-African Orogeny resulted from collision of the West African craton with the East Saharan craton during the assembly of Gondwana. Proterozoic rocks now exposed in the Hoggar Massif to the south of the Berkine sub-basin display major north-south striking fault systems that juxtapose metamorphic basement blocks of varying compositions. These fault blocks are unconformably overlain by basal Paleozoic sediments, confirming a pre-Paleozoic age of faulting. We speculate that the Pan-African fault systems continues to the north below the Berkine sub-basin, and that the location, orientation, and sense of motion of subsequent faulting during the Phanerozoic was strongly influenced by trends established during this early orogenic event.

The Cambrian through Carboniferous was a time of relative quiescence, with basin subsidence interrupted only by minor Ordovician and Silurian compressional events. These resulted in localized unconformities, the most prominent of which is the Caledonian Unconformity during the latest Silurian. This event is characterized by low amplitude folding and faulting as evidenced by a number of the fields in the Illizi basin to the south.

2. *Technological advances in acquisition and processing have greatly enhanced the quality of seismic data, as illustrated by these two seismic images.*

The Hercynian Orogeny was the collision of Gondwana with Laurentia during the Permian. This resulted in major tilting, uplift and erosion of the Paleozoic section. In the Berkine sub-basin, estimates of removed overburden based on stratigraphic projection and matching sonic logs with compaction curves range from 2400 meters in the southeast to 5500 meters in the northwest. Despite the significant magnitude of uplift, it remains uncertain if there was active faulting in the Berkine sub-basin during this time period.

During the Triassic and Early Jurassic, the opening of Tethys and the Atlantic resulted in subsidence, tilting, and regional extension of the Paleozoic section. Faults of this age strike north to northeast and define a series of uplifted and tilted fault blocks. There is a consistent spacing of about 40 kilometers between these blocks as well as a progressive reduction in the amplitude of faulting towards the east. South of the Berkine sub-basin where Paleozoic and pre-Cambrian rocks are exposed at the surface, inspection of published maps suggests that Triassic aged faults in the Paleozoic section are frequently localized above pre-existing faults in the Precambrian. Boudjema (1987) proposed a slipline model of Pan-African faulting that closely approximates the major Triassic fault trends in the Paleozoic section of the Berkine sub-basin. Also, we note that the orientation of Triassic faulting is not parallel to either the Atlantic margin or the Tethyan margin. Taken together, these observations lead us to speculate that the Pan-African fault system was reactivated by Triassic and Early Jurassic extension, possibly with a component of strike slip motion.

Cretaceous and younger deformation in the Berkine sub-basin is associated with the Austrian, Pyrenian, and Alpine Orogenic events. These represent different stages in the collision of Africa with Europe and the opening of the Mediterranean. Both compressional and extensional faulting is documented during the Cenozoic, with minor normal faulting evidenced in late Cretaceous and older sediments, and compressional inversion of Triassic aged normal faults effecting Miocene sediments. A major unconformity occurs at the base of the Paleocene with estimates of erosion ranging from zero to over three kilometers depending on location and the technique used to estimate removed overburden.

Characterization of Trap Style

Six prominent producing trends have been identified in the Berkine sub-basin: (1) the major Anaguid-El Biod trend; (2) the Nezla-Rhourde El Baguel trend; (3) the Gassi Touil trend; (4) the Rhourde Nouss-Brides trend; (5) the Hassi Berkine-El Borma trend; and (6) the minor Choueche Essaida trend in Tunisia. Each producing trend is associated with an uplifted block bound by a system of north to northeast trending faults of Triassic or Early Jurassic age. The main bounding faults are clearly visible on 2D seismic data at the Ordovician and middle Devonian levels. Historically, exploration along these semi-regional horst blocks has produced successful results.

The newly discovered fields sit on low relief tilted fault blocks along the crest of the semi-regional horsts. The dominant fault trend at the field scale is parallel to the semi-regional horst bounding fault system and is of Triassic or Early Jurassic age. The spacing of these faults and the magnitude of their offset plays a large role in determining the field size, but they strike parallel to the direction of regional dip and do not provide up-dip closure for the hydrocarbon accumulations. Up-dip closure is defined by a series of northwest-southeast striking synclines that cross cut the major structural grain and a set of east-west striking down-to-the-north normal faults (figure 3). The age and tectonic affinities of the synclines remain ambiguous. Isopach analysis indicates that they were present during the early Paleozoic and were reactivated during the Triassic and Jurassic. The east-west trending faults are Late Cretaceous or younger.

3. Schematic map of the Hassi Berkine South Field (HBNS) showing tilted fault blocks and synclinal closure to the northeast.

Conclusions

The key component to exploration success in the Berkine sub-basin has been identification of semi-regional horst blocks. We speculate that these uplifted fault bounded blocks formed through reactivation of the Pan-African fault system, and we have observed that fault offset is largest along the Anaguid-El Biod producing trend and decreases in amplitude to the east. Advances in seismic imaging technology have enabled smaller relief structural features to be imaged where they were not evident previously. Individual hydrocarbon accumulations occur along these semi-regional horsts where three distinct structural trends intersect to create local traps.

We speculate that the Anaguid-El Biod trend overlies one of the major spines emanating from the core of the Pan-African collision, and that there may be a series of reactivated horst blocks in the poorly explored region to the west of the Anaguid-El Biod trend that mirror productive features in the Berkine sub-basin. The basic concept of how multiple phases of deformation interact in a constructive manner to produce

structural traps may be applied to other basins in the circum-Mediterranean region that have experienced a similar tectonic history.

References

Boudjema, A., Evolution Structurale du Bassin Pétrolier "Triasique" du Sahara Nord Oriental (Algerie), Doctoral Thesis, University de Paris-Sud, Centre d'Orsay, 1987