INTRODUCTION

Discovery of giant oil and gas fields are significant events to the petroleum geoscientist. Successful drilling of a giant hydrocarbon accumulation validates the petroleum geoscientist's work and ensures the basin or province will become a major producing area in the world. Prediction of such areas in advance of the drill bit is however full of risk. During 1977, Petroleum Publishing Company published a special issue of the Oil and Gas Journal to commemorate its 75th anniversary. The issue, entitled PETROLEUM 2000, presented a series of papers which attempted to visualize future opportunities of the petroleum industry. In a review of future onshore petroleum opportunities, Meyerhoff (1977) predicted a number of traps remained to be discovered in Algeria, Libya, and Egypt. Although acknowledging the possibility of several undiscovered giant fields in northern Africa, he suggested accumulations would be smaller than those producing in 1977 and only marginally commercial. With renewed exploratory drilling in Algeria during the 1990's, Algeria ranked first in the world in 1994 with 1.1 billion barrels of oil discoveries (Anonymous, 1997). The majority of these new reserve additions were the result of exploration within the Berkine Basin portion of the greater Ghadames Basin. To date, exploration of the Berkine Basin during the 1990's has discovered in excess of 2 billion barrels of recoverable oil. Although individual field reserves remain proprietary, Macgregor (1998) indicates at least three of the Berkine Basin discoveries have reserves exceeding 250 MMBOE and two of the discoveries have between 500 and 1000 MMBOE. The three discoveries, Hassi Berkine North, Hassi Berkine South, and El Merk were the result of an intensive exploration effort by Anadarko Petroleum Corporation and its partners Sonatrach Oil and Gas, Lasmo Oil, and Maersk Oil and Gas. One additional field discovered by the Anadarko group in 1994, Ourhoud (the field formerly known as Qoubba), has reserves in excess of 1.1 billion barrels of oil (Anonymous, 1999). Thus an understanding of the Anadarko group's exploratory process and its evolution provides insight into the remaining undiscovered hydrocarbon potential of the Berkine Basin.

LOCATION

The Berkine Basin, located in extreme eastern Algeria (Figure 1), is the westernmost extension of the larger Ghadames Basin. The Ghadames Basin, a peri-cratonic basin with a polyphase tectonic history, covers approximately 350,000 square kilometers in eastern Algeria and parts of Tunisia and Libya and contains over 6000 meters of Paleozoic and Mesozoic siliciclastic-dominated sediments (Echikh, 1998). Located within the Grand Erg Oriental portion of the Sahara Desert, the Berkine Basin is characterized on the surface by extensive areas of eolian sand dunes greater than 300 meters in height and intervening areas of gravel pavement. Petroleum infrastructure, roads, and centers of population are developed only along the northern, eastern, and southern portions of the Grand Erg Oriental. Within the subsurface, the Berkine Basin is structurally bounded on the northeast by the Damah Zone and the northwest and west by the Hassi Messaoud Ridge. It is separated from the Illizi Basin on the south by the Mole D'Ahara. Surrounding the Berkine Basin and on its western flank are a series of giant oil and gas fields including Rhourde El Baguel, Gassi Touil, Tin Fouye-Tabankort, and Alrar (Figure 1). The super-giant Hassi Messaoud oil field is located approximately 160 kilometers northwest of the Berkine Basin. El Borma field, straddling the Algerian-Tunisian border is located in the northeast portion of the Berkine Basin.

BASIN ARCHITECTURE AND DISTRIBUTION OF OIL AND GAS

With renewed interest in exploration of the Berkine Basin during the 1990's, various aspects of the Berkine Basin petroleum geology have recently been summarized in a series of papers on the basin's structural evolution (Gauthier et al, 1995; Sonatrach, 1995; Boote et al, 1998; Echikh, 1998; and Guiraud, 1998), and petroleum systems (Daniels and Emme, 1995; Boote et al, 1998; and Macgregor, 1998). Echikh (1998) provides a comprehensive synthesis of the Berkine Basin's petroleum geology. Detailed description of the Phanerozoic sediment package, development and geographic extent of hydrocarbon-charged reservoirs, and their chronostratigraphy is incompletely known. Sonatrach (1995), Echikh (1998), and Fekirine and Abdallah

(1998) provide summaries of the Phanerozoic sediment package and its reservoir potential. Details on many o potential and proven hydrocarbon-bearing reservoirs remain to be worked out and will require additional exploratory drilling. A generalized stratigraphic column for the Berkine Basin is shown in Figure 2.

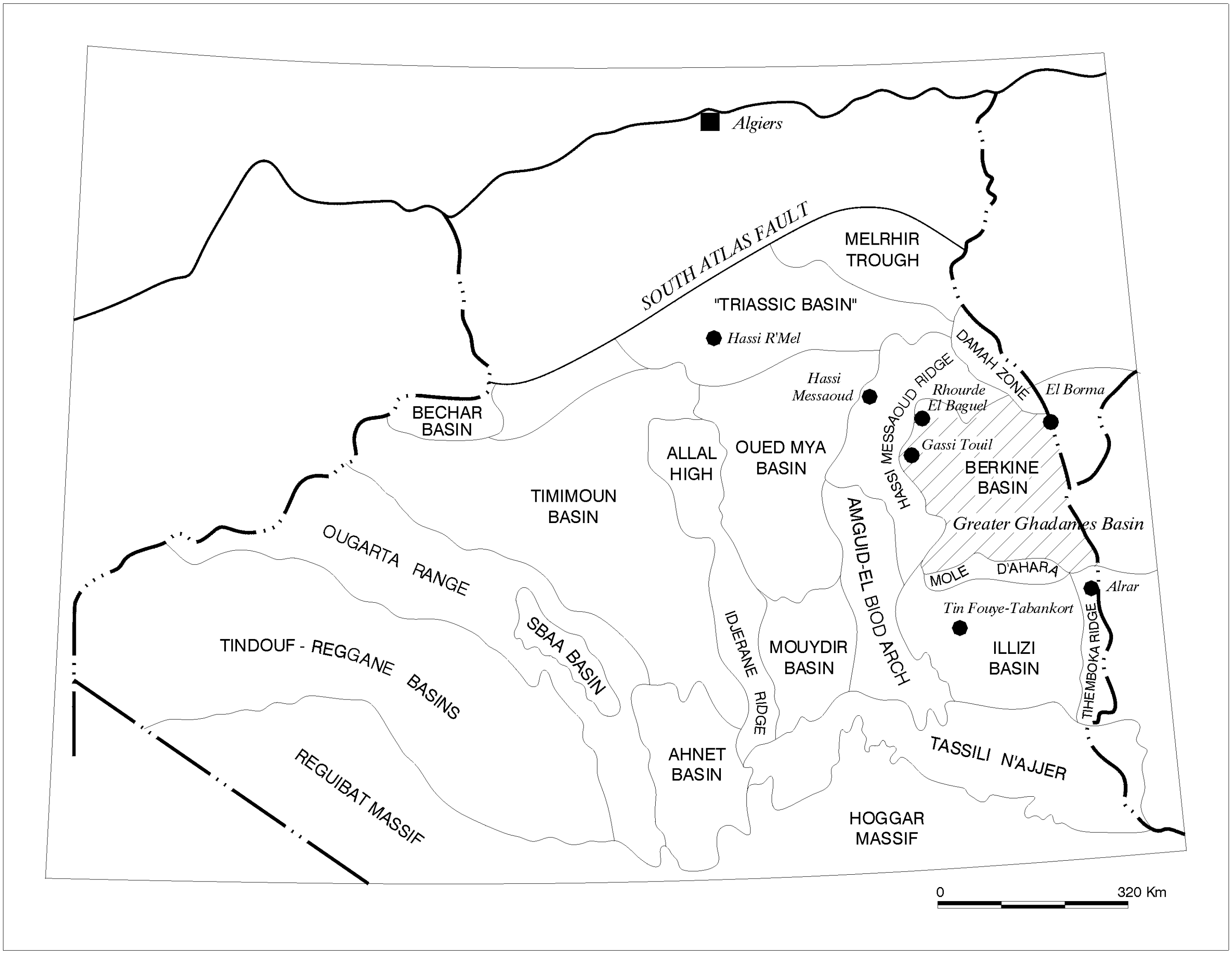

Figure 1

Figure 1. Tectonic elements map of Algeria showing location of Berkine Basin. Filled circles represent locations of giant oil and gas fields.

Figure 3 illustrates the distribution of oil and gas accumulations within the Berkine Basin and portions of the bounding Hassi Messaoud Ridge and Mole D'Ahara/Illizi Basin. Hydrocarbon accumulations are presently restricted to the west and north portions of the basin and are closely related to truncation edges of various Paleozoic intervals. Structurally, the Berkine Basin is a part of the Central Saharan Platform which has undergone a complex and polyphase evolution and been influenced by Pan African brittle basement fracturing. This portion of the Central Saharan Platform is the site of a series of structural arches and continental highs (moles) which have controlled sedimentation and thus the deposition of hydrocarbon source rocks, reservoirs and seals. Tectonic features have been affected by nine major tectonic phases ranging in age from Precambrian to Tertiary. Pre-Hercynian tectonic activity in the Early Ordovician (Taconic tectonic phase) and Late Silurian-Early Devonian (Caledonian tectonic phase) caused uplifting and erosion on the southwestern and southern flanks of the Berkine Basin (Echikh, 1998) and is responsible for the depositional geometry of Early Paleozoic reservoir intervals and maturation history of the Early Silurian source rock interval. Hercynian (Carboniferous through Middle Triassic) tectonic activity and accompanying erosion is responsible for the present-day truncated distribution of the Paleozoic along the western and northern portions of the basin (Figure 3) as well as destruction of some pre-Hercynian oil filled traps. Topographic relief created on the Hercynian Unconformity also plays a major role in the deposition of Late Triassic sediments within the Berkine Basin. Mesozoic tectonic events including Triassic-Liassic rifting, Early Cretaceous (Austrian tectonic phase) and latest Eocene (Pyrenean tectonic phase) structural movement strongly influenced formation of hydrocarbon-charged traps, Mesozoic seal development, and maturation history of Late Devonian source rock.

Figure 2. Generalized stratigraphic column for Berkine Basin showing position of producing reservoirs, source rocks, regional seals, and Hercynian Unconformity.

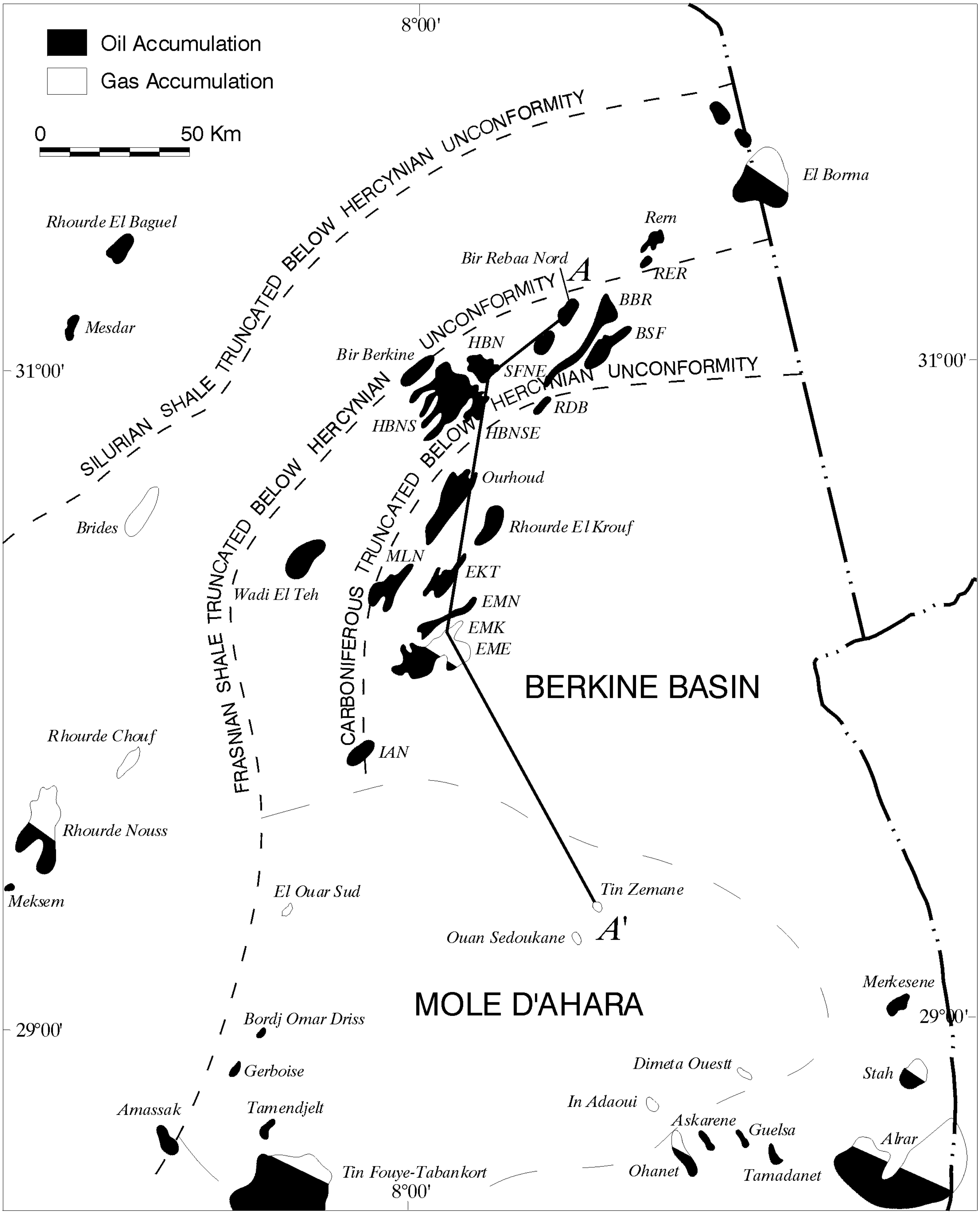

Figure 3

Figure 3. Geographic distribution of oil and gas accumulations within Berkine Basin, northern portion of Illizi Basin, and eastern portion of Amguid-El Biod Arch and Hassi Messaoud Ridge.

Stratigraphic nomenclature and chronostratigraphy of the Paleozoic and Late Triassic Berkine Basin sediment pile is in a state of transition. Application of sequence stratigraphic concepts to Paleozoic and Early Mesozoic intervals has only recently been initiated (Ford and Scott, 1997; Scott et al, 1997; Fekirine and Abdallah, 1998; Nykjaer, 1998, personal communication) and basin-wide biostratigraphic correlation of the Paleozoic is in its infancy. Biostratigraphic correlation of the Late Triassic non-marine section is hampered by poor to sparse recovery of diagnostic palynomorphs. A unified stratigraphic nomenclature for the Berkine Basin Paleozoic and Late Triassic is yet to be accomplished. Present nomenclature within the Paleozoic is a mixture of outcrop terminology from the Tassili N'Ajjer (Figure 1) and informal naming of hydrocarbon-producing reservoir intervals within the Illizi Basin. Correlation and extension of the Tassili N'Ajjer outcrop and Illizi Basin subsurface stratigraphic succession into the Berkine Basin is complicated by rapid thickening of the Paleozoic interval into the basin and sparse well control penetrating Early Silurian and older-aged sediments. The Anadarko group's electric log database does, however, allow reasonably reliable wireline correlation over much of the sedimentary section. Figure 4 is a generalized Paleozoic chronostratigraphic cross-section along the western portion of the Berkine Basin. The influence of the Hercynian Unconformity on preservation of Middle Devonian through Middle Triassic sedimentation is evident on the northern end of the section where in excess of 150 million years of geologic record is missing. Carboniferous sedimentation is preserved only in the central portion of the basin. Absence of a Carboniferous rock record on the southern end of the cross-section is related to the presence of the Mole D'Ahara, a continental high which persisted throughout most of the Paleozoic and well into the Mesozoic. Overall non-marine deposition and significant facies changes from the northern to southern portion of the Berkine Basin within the Late Triassic hamper correlation of this important hydrocarbon-bearing interval.

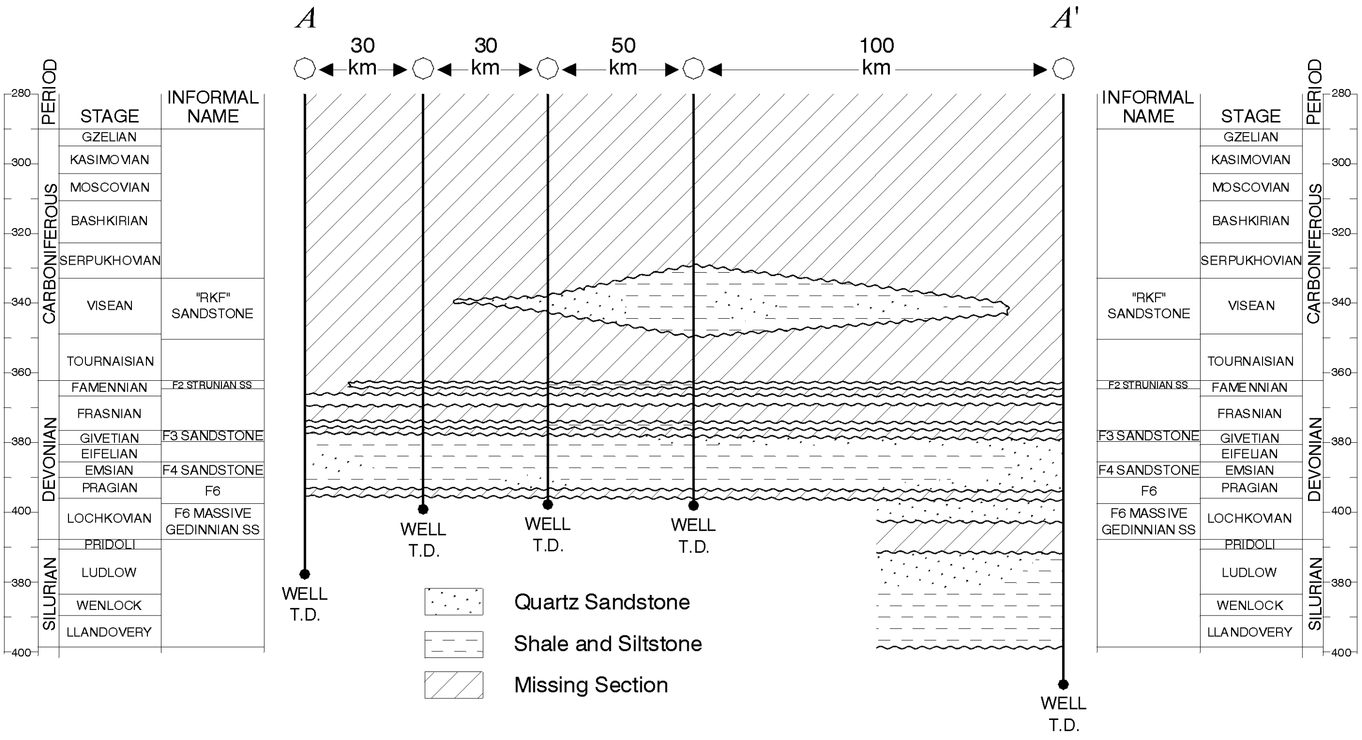

Figure 4

Figure 4. Paleozoic chronostratigraphic cross section across western portion of Berkine Basin showing temporal and geographic distribution of Silurian, Devonian, and Carboniferous sedimentary packages. Line of section (A-A') illustrated on Figure 3.

EVOLUTION OF THE ANADARKO GROUP'S EXPLORATION PROGRAM

The Anadarko group's exploration effort has evolved along three lines. They include: (1) Continuing development of a basin-wide petroleum system and structural model, (2) Increased improvement of the seismic tool as the primary method of prospect generation and field development, and (3) Continuing development of cost-saving measures associated with increased drilling efficiency. Beginning in 1986, Anadarko's early exploration efforts in conjunction with block selection focused on identification of structural traps and improvement of seismic imaging. Potential exploratory targets included the Trias Argilo Greseux Superieur (T.A.G.S.), Trias Argilo Greseux Inferieur (T.A.G.I.) and Siluro-Devonian F6 quartz sandstones. Although Upper Devonian (Frasnian) radioactive shales were recognized during these evaluations as a potential hydrocarbon source, Early Silurian (Llandovery) radioactive shales were considered to be a primary hydrocarbon source. Attention rapidly focused on a potential 4-way closure of 138 km2 in the northwestern portion of the Berkine Basin. The structure was located 26 kilometers east of Brides Field and 27 kilometers west of Wadi El-Teh (Figure 3), west of the Frasnian radioactive shale truncation and east of the onset of Silurian truncation. With the drilling of the BKW-1 exploratory well and its abandonment in 1991, the Anadarko group focused its attention on a series of technical evaluations to better understand source rock quality and distribution and general migration pathways. The BKW-1 well is noteworthy for its lack of hydrocarbon shows and reservoir quality quartz sandstones in Triassic and Siluro-Devonian intervals. Building on Boudjema's (1987) work, it was quickly demonstrated the BKW structure occupied a regionally structural low position within the basin at the time of peak hydrocarbon migration which precluded significant migration of hydrocarbons into the structure. Mapping of Frasnian and Llandovery radioactive shales organic carbon content, kerogen type, and maturity forced a reassessment of potential areas for exploration within the Berkine Basin and focused the group's attention to areas in a more optimal "fetch" position than the BKW structure. With announcement of Cepsa's discovery at Rhourde El Krouf in 1992 and successful completion of the Anadarko group's well at EMK in 1993 (Figure 3), additional hydrocarbon-bearing reservoirs and significance of faulting in hydrocarbon migration were recognized. Detailed studies on the T.A.G.I. siliciclastic system were undertaken in 1994 and continue today. Initial studies on the Berkine Basin Devonian and Carboniferous biostratigraphy, sequence stratigraphy, and deposition were initiated during the period 1995-1997. In conjunction with Institut Francais du Petrole, the Anadarko group initiated 2D Temispack and Temiscomp basin modeling in 1995 to assist in predicting hydrocarbon migration pathways and timing and hydrocarbon composition of the reservoirs. A portion of this study was published by Rudkiewicz et al (1997). As the Anadarko group's understanding of the Berkine Basin evolved, the exploratory drilling program resulted in an additional 13 discoveries (11 Anadarko group operated). Flow rates up to 21,395 BOPD have been recorded from the Triassic section. Strunian and Visean reservoirs have recorded flow rates up to 53.6 MMCF/D and 5,508 barrels of condensate per day.

During Anadarko's initial visit to Sonatrach's offices in 1986, evaluation of seismic data indicated existence of severe statics problems associated with dynamite acquisition in the loosely packed, unconsolidated surface sand section. Additionally, the size of the sand dunes covering the surface of the Berkine Basin did not allow for "straight" line seismic acquisition. Correct processing of "crooked" line seismic needed to be applied. Seismic misties caused by navigational errors were also common. Based on these initial observations, the Anadarko group reprocessed 36,000 kilometers of Sonatrach 12-fold stack 2D seismic data. Examples of unreprocessed and reprocessed Sonatrach data are shown in Figure 5. The Anadarko group's strategy was to reprocess Sonatrach data, identify prospective areas, and supplement existing data with additional seismic acquisition. Early exploration was directed towards late inversion structures as they were the only structures visible on the seismic data. Such traps were inherently high risk due to late structural movement. Later exploration concentrated on early-formed structures, facilitated by dramatic improvements in the resolution of the data. During the reprocessing effort, it became apparent that reprocessed data was insufficient to identify with any degree of confidence potential drilling locations. The decision was made in 1990 to acquire an entire new grid of 2D seismic. Feasibility studies indicated alternative sources to employment of conventional surface dynamite as an energy source for seismic acquisition were warranted. Therefore, the Vibroseis technique was chosen as the energy source for new acquisition. Between 1990 and 1993, the Anadarko group acquired 6,718 kilometers of 120-fold seismic data. Two-D seismic acquisition resumed in 1994 with acquisition of 2,188 kilometers of 240-fold seismic data between 1994 and 1997. Examples of 120-fold and 240-fold data are illustrated in Figure 6. Beginning in 1995, feasibility and optimization studies for acquisition of 3D seismic were initiated. Based on these studies 3D seismic acquisition started in 1996. To date, 1,634 square kilometers of 3D seismic have been acquired. Additional 3D seismic acquisition is underway. An example of 3D seismic is shown in Figure 6.

Concurrent with basin studies and geophysical evaluations, substantial reductions in the cost of drilling wells were implemented. The need for costly, permanent road construction into remote locations was eliminated. Drilling rig mobilization was accomplished directly across the sand dunes. Efficiencies in bit selection, drilling fluids, and hole size resulted in a dramatic decrease in time necessary to drill wells (Figure 7). The Anadarko group's first well (BKW-1) took in excess of 175 days to drill and evaluate. By 1996, drilling time for a well of comparable depth was less than 80 days. Field development wells at HBNS are now being completed in a time frame of less than 20 days to total depths of 2900 meters.

BERKINE BASIN PETROLEUM SYSTEM COMPONENTS

Source Rocks

The most comprehensive evaluation of source rock within the Berkine Basin is by Daniels and Emme (1995). Based on organic richness and thermal maturity analysis of over 3900 rock samples from 84 wells and oil-oil correlation of samples from 24 fields, they concluded Early Silurian (Llandovery) Silurian Argileux and Argiles a Graptolites and Middle to Late Devonian (Givetian through Famennian) Serie de Tin Meras shales were the source for hydrocarbons trapped within the Berkine Basin. Later work by Zumberge et al (1996), Illich et al (1997), and Makhous et al (1997) at least partially supported their conclusions. Recognition of Llandovery graptolitic shales as a source for reservoired hydrocarbons within the Illizi Basin was reported by Tissot et al (1984).

Highest Total Organic Carbon (TOC) content within the Early Silurian and Late Devonian shales are concentrated in two discrete intervals. Highest TOC content (2 to >17%) within the Early Silurian shale section is consistently found in the Llandovery basal radioactive shale interval. Late Devonian maximum TOC content (8 to 14%) is found within Frasnian radioactive shales. Kerogen facies in Llandovery and Frasnian radioactive shales are generally oil-prone with type I/II content. Present-day geographic distribution of Llandovery and Frasnian radioactive shales within the Berkine Basin is controlled by Hercynian-aged erosion on the north and west flanks of the basin. Within the central portion of the basin, Frasnian radioactive shales exceed 200 meters in thickness while Llandovery radioactive shales vary from 25 to 35 meters. Frasnian radioactive shales thin to less than 50 meters across the Mole D'Ahara. TOC quality and thickness varies more regionally for Frasnian radioactive shales than Llandovery radioactive shales.

Mapping of "equivalent" vitrinite reflectance indicates Llandovery radioactive shales are in the wet to dry gas window (1.75 to 2.0 Ro%) within the central portion of the basin. In the northern portion of the basin near El Borma Field, and on the Mole D'Ahara (Figure 3), Llandovery radioactive shales are within the peak to late oil generation window (0.8 to 1.2+ Ro%). "Equivalent" vitrinite reflectance data for Frasnian radioactive shales demonstrates the interval is within the late oil to early wet gas generation window (1.1 to 1.4 Ro%) for the central portion of the Berkine Basin. In the northern portion of the basin, south of El Borma Field, and over the Mole D'Ahara, Frasnian radioactive shales are in the early to peak oil generation window (0.5 to 1.1 Ro%).

Figure 5. Comparison of 1973 Sonatrach acquired 12-fold stack seismic (top seismic line) and reprocessed version of same line (bottom seismic line) by Anadarko group.

Figure 6. Comparison of 1992 acquired and processed 120-fold stack seismic (top seismic line), 1994 acquired and processed 240-fold DMO stack seismic (middle seismic line) and an arbitrary line from a 3D volume (bottom seismic line). Compare with Figure 5.

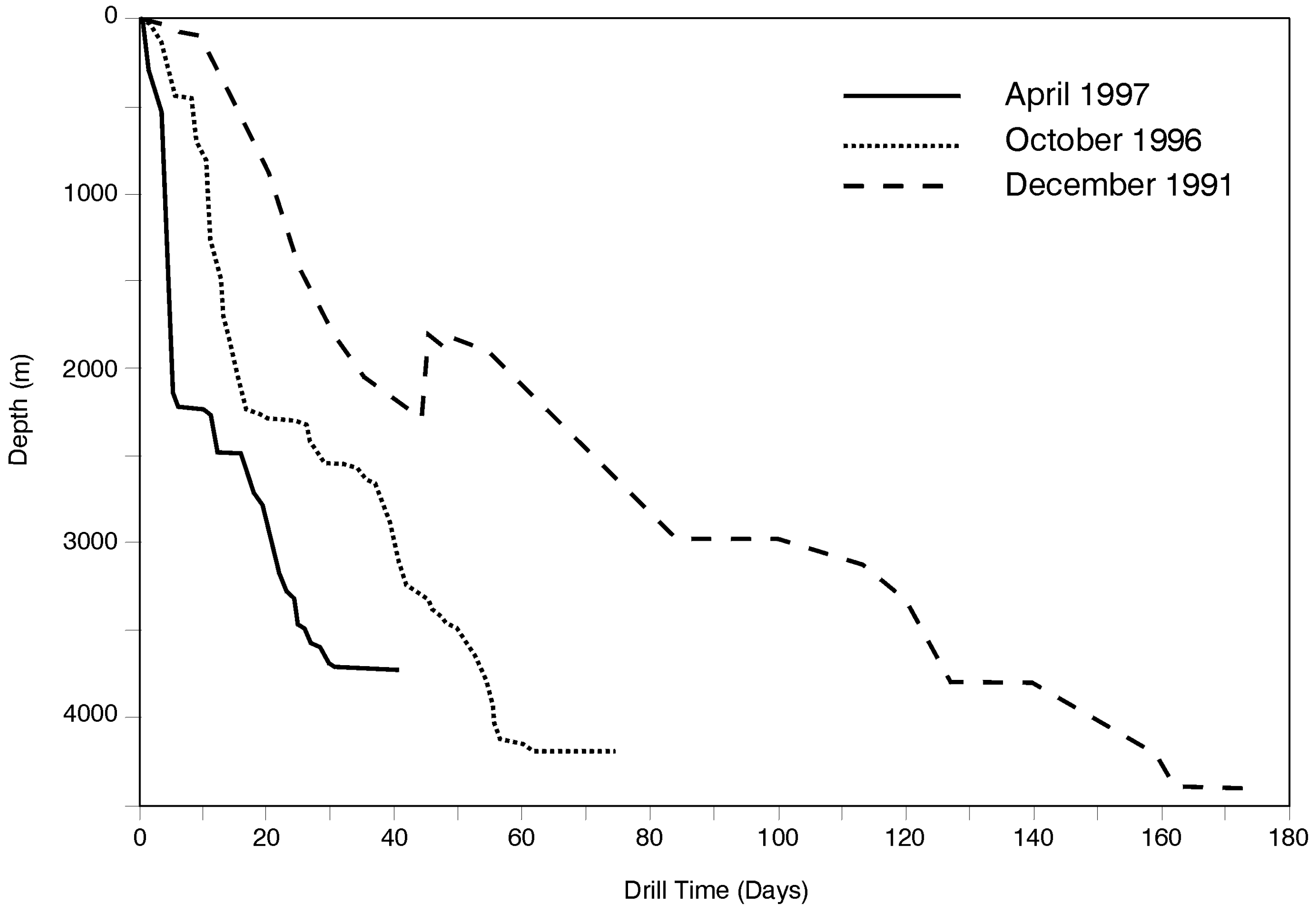

Figure 7

Figure 7. Plot of drill time (days) versus depth (meters) for wells drilled by the Anadarko group in 1991, 1996, and 1997. Drilling time for wells of comparable depth decreased from over 170 days in 1991 to under 80 days in 1996. By 1997, wells drilled to within 500 meters of 1996 well decreased to under 50 days.

Based on one-dimensional kinetic simulations for 22 wells within the Berkine and Illizi basins, Daniels and Emme (1995) calculated timing of peak oil generation for Llandovery basal radioactive shales and Frasnian radioactive shales. Figure 8 summarizes Daniels and Emme's (1995) interpretation of areas of peak oil-generative timing for Llandovery basal radioactive shales. The central portion of the Berkine Basin and eastern portion of the Illizi Basin reached peak oil generation from Early Carboniferous to Late Jurassic. This is indicative of pre- and post-Hercynian oil generative phases. Traps filled prior to the Hercynian tectonic phase have probably been destroyed in areas of significant Hercynian erosion. The northern portion of the Berkine Basin reached peak oil generation beginning in the Mid-Cretaceous (approximately 125 million years before present) and has continued to present. The most significant quantity of oil generated was probably during the last 65 million years (Daniels and Emme, 1995). The southwestern portion of the Berkine Basin and the area across the Mole D'Ahara has a broad oil generative history which ranges from Late Carboniferous to present. The main generative phase appears to be Mid-Cretaceous (Daniels and Emme, 1995). Frasnian radioactive shales exhibit nearly the same pattern for areas of peak oil-generation (Figure 9) with all timing shifted to post-Hercynian. The northern portion of the basin reached the oil generation window in Early Tertiary and is presently at or near peak generative capacity (Daniels and Emme, 1995). Timing of peak oil generation within the deepest portion of the basin was from Late Triassic through Mid-Jurassic.

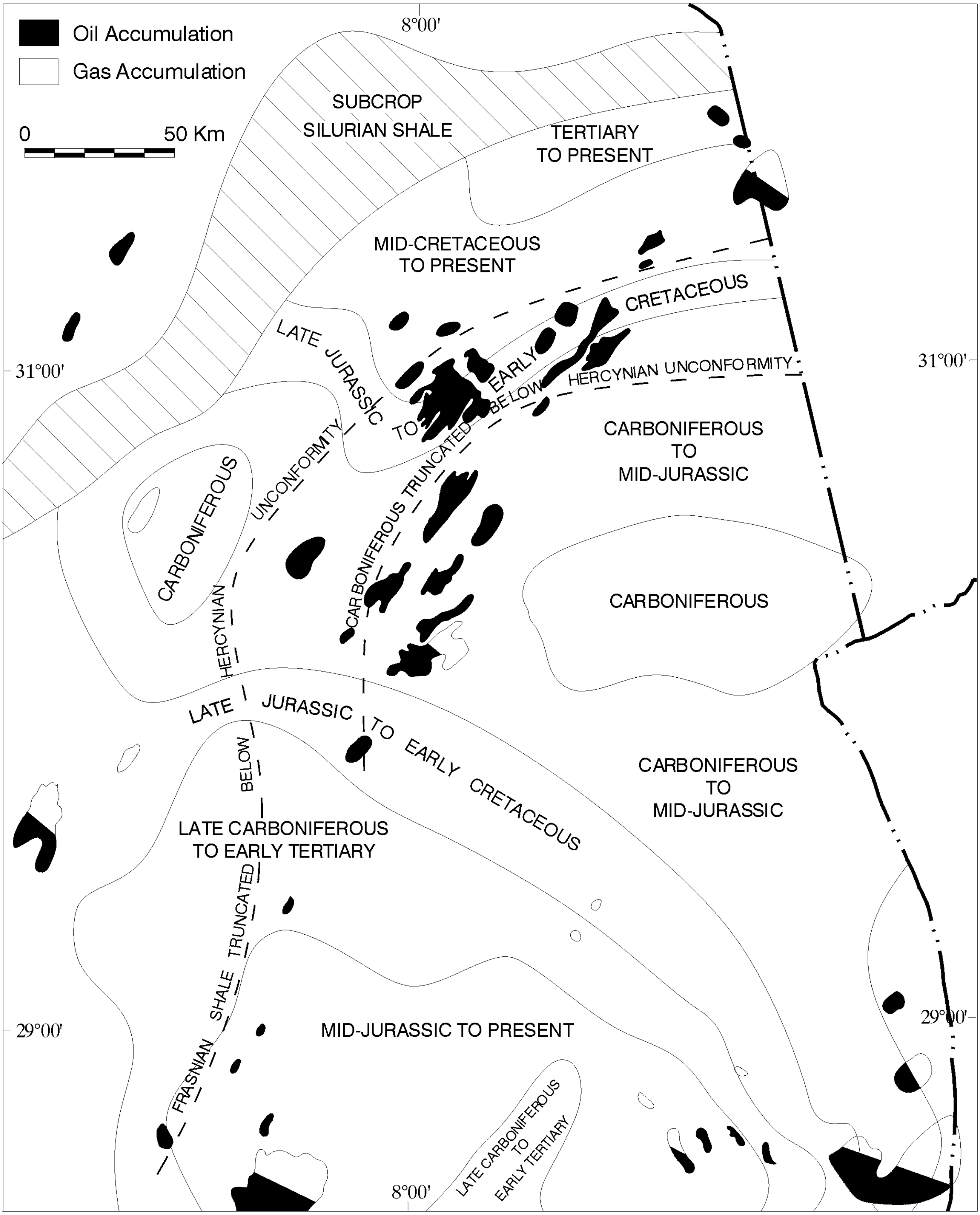

Figure 8

Figure 8. Peak oil generation timing map of Early Silurian (Llandovery) radioactive shales in Berkine Basin and northern portion of Illizi Basin. (Modified from Daniels and Emme, 1995).

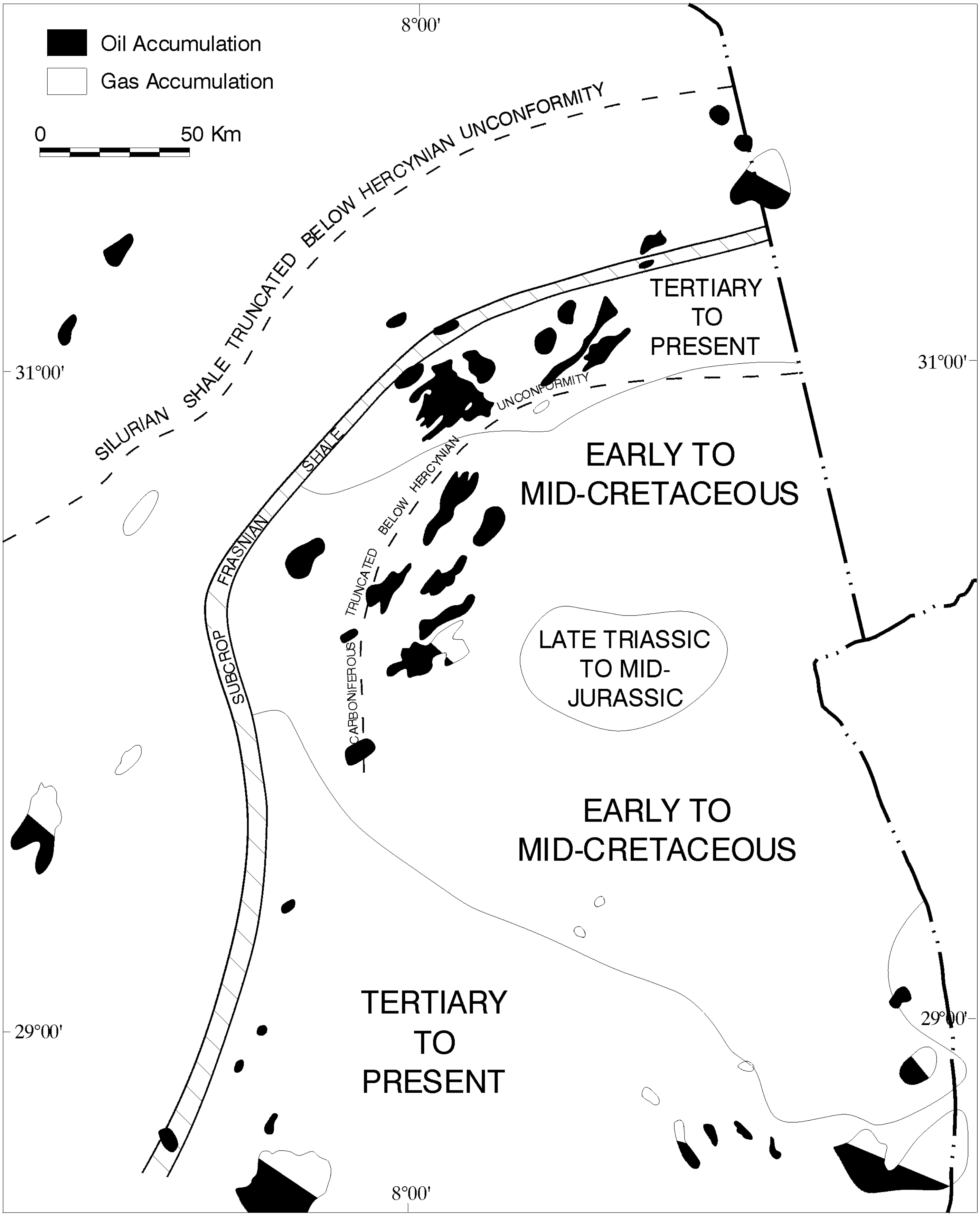

Figure 9

Figure 9. Peak oil generation timing map of Late Devonian (Frasnian) radioactive shales in Berkine Basin and northern portion of Illizi Basin. (Modified from Daniels and Emme, 1995).

Based on compositional analysis of oils from 24 fields, high resolution gas chromatography and liquid chromatographic separation, Daniels and Emme (1995) concluded the oils are highly mature and sourced by a similar kerogen type which is characteristic of Llandovery basal radioactive shales and Frasnian radioactive shales. The oils do not correlate with any of the Ordovician, Silurian, latest Devonian (Famennian), Carboniferous, or Mesozoic shale samples analyzed (Daniels and Emme, 1995). Two-genetically-related families of oils can be discriminated. The first family, located north and west of the Frasnian radioactive shale truncation line (Figures 3 and 9) is most likely sourced from Llandovery basal radioactive shales. Reservoired oil south and east of the Frasnian radioactive shale truncation line (Figure 9) is a mixture of Llandovery and Frasnian sourced oil.

Calculations of generated oil volumes indicate Frasnian radioactive shales generated in excess of 700 billion barrels of oil within the Berkine and Illizi basins. Llandovery basal radioactive shales generated over 1400 billion barrels of oil (Daniels and Emme, 1995). These volumes are consistent with calculations made by Anadarko for other world class petroleum systems (i.e. Ellesmerian of the North Slope, Alaska).

Hydrocarbon Reservoirs

Hydrocarbon-producing reservoirs within the Berkine Basin range in age from Lochkovian (Early Devonian) through Carnian (Late Triassic) and are siliciclastic in composition. Present-day distribution of Lochkovian (Early Devonian) through Visean (Early Carboniferous) reservoir intervals is controlled by amount of Hercynian erosion on the north and west flanks of the basin and by paleotopographic expression on the Mole D’Ahara to the south. Pre-Lochkovian production exists along the flanks of the Berkine Basin. Ordovician siliciclastics produce gas at Brides Field (Arenig - Hamra Quartzite) on the west flank of the Berkine Basin and oil and gas at Tin Fouye-Tabankort Field (Ashgill through Llandovery – Unit IV) in the Illizi Basin (Figure 3). Acacus Formation siliciclastics (Silurian Wenlock through Pridoli) produce oil and gas in the Tunisian and Libyan portions of the Ghadames Basin. Equivalent quartz sandstones to the lower portion of the Acacus (lower F6 of Algeria) produce from numerous fields in the Illizi Basin. Cambro-Ordovician (Upper Cambrian to Early Ordovician Tremadoc-Arenig) quartz sandstones are the primary producing oil reservoirs at the super giant Hassi Messaoud Field to the northwest of the Berkine Basin (Figure 1). Hydrocarbon potential of the pre-Lochkovian section within the Berkine Basin is unknown at present time due to sparseness of penetrations.

Lower and Middle Devonian (Lochkovian through Givetian/Eifelian) siliciclastic reservoirs represent deposition in coastal plain to marine settings. Stratigraphic position of producing reservoirs is shown in Figure 10. Stratigraphic nomenclature for these reservoirs is from the Illizi Basin. Although Berkine Basin Lower and Middle Devonian reservoirs correlate in a general way with the Illizi Basin section, accurate chronostratigraphic correlation requires further study.

Lochkovian F6 massive quartz sandstones (Figure 10) are present throughout the Berkine Basin. On the western and northern flanks of the basin, F6 massive sandstones are truncated by Hercynian erosion. Present-day maximum F6 quartz sandstone thickness is in the northern part of the basin (Figure 11). Porosity values in excess of 20% are found in the northern portion of the basin and within the eastern portion of the Illizi Basin. Within the central portion of the Basin, porosity values for non-argillaceous massive F6 quartz sandstones range from 12 to 18% (Figure 11). Although there is general correlation between grain-size and reservoir quality (Figure 12), the dominant limiting factor in reservoir quality is the presence of pore-lining ferriferous chlorite cement. Presence of pore lining chlorite cement preserves high porosity (>20%) and permeability (>1000 millidarcies) at depths greater than 4700 meters (Figure 13). Where pore-lining chlorite cement is not present, porosity is reduced by compaction and quartz overgrowths to less than 10% (Figure 13). Permeability is reduced to less than 5 millidarcies. Bekkouche et al (1993) calculate timing of formation of chlorite pore-lining cement at approximately 283 million years before present based on potassium/argon dating. Formation of chlorite pore-filling cement is apparently related to the Hercynian tectonic phase. Additional Lower Devonian

(Pragian through Emsian) hydrocarbon-producing reservoirs are present within the Illizi Basin and northwestern portion of the Berkine Basin. Fine-grained to very fine grained, laminated quartz sandstones, correlated with the F6 "C" sandstone of the Illizi Basin (Figure 10), are the primary reservoir at Sonatrach's Bir Berkine Field (Figure 3). Secondary reservoirs at Bir Berkine Field have been correlated with the Illizi Basin F6 "A & B" quartz sandstones (Figure 10). Nykjaer (1998, personal communication) interprets the Bir Berkine Pragian quartz sandstones as part of a prograding deltaic complex. Reservoir properties are fair. Porosities can exceed 20% but due to the fine-grained nature of the sandstone, permeability is limited to less than 100 millidarcies. Emsian fine-grained quartz sandstones, productive at Bir Rebaa Nord Field (Figure 3), are apparently equivalent to the F4 reservoir interval of the Illizi Basin (Figure 10). They have been penetrated only in the north and northwestern portions of the Berkine Basin and in the Illizi Basin. Nykjaer (1998, personal communication) interprets the Bir Rebaa Nord quartz sandstones as indicative of wave-dominated shoreface deposition.

Middle Devonian (Eifelian through Givetian) F3 reservoirs (Figure 10) are productive at Alrar Field on the east side of the Mole D'Ahara within the Illizi Basin (Figure 3). Chaouchi et al (1998) interpret productive siliciclastic intervals at Alrar as a series of tidally influenced barrier bars. Typical bar facies porosities range from 7 to 15%. Permeabilities range from 5 to 43 millidarcies (Chaouchi et al, 1998). F3-equivalent quartz sandstones are present along the north flank of the Mole D'Ahara. They are not present on the Mole D-Ahara where their disappearance is a combination of depositional thinning of the F3 interval and local erosion over depositional highs. Nykjaer (1998, personal communication) suggest longshore drift is responsible for re-deposition of F3 quartz sandstones north of the Mole D'Ahara in a progradational sequence. F3-equivalent quartz sandstones pinch out northward towards the central portion of the Berkine Basin.

Prior to Cepsa's discovery of Rhourde El Krouf Field (Figure 3) in 1992, the youngest Paleozoic interval containing reservoir quality quartz sandstones observed in the Berkine Basin was the lowermost Strunian (latest Devonian) F2 interval (Figure 14). F2 sandstones are productive in the Illizi Basin where porosities reach 18% and permeabilities up to 1000 millidarcies have been recorded (Sonatrach, 1995). Cepsa's discovery well, RKF-1, penetrated several thick Visean (Early Carboniferous) and Strunian (latest Devonian) quartz sandstone packages (Figure 14) which were informally termed the "RKF" and "Strunian beach" sandstones. The regional nature of these previously unknown sandstone packages was confirmed in 1993 by Anadarko's EMK-1 well. Strunian and Visean quartz sandstone packages represent a continuum of environments ranging from shoreface through wave-dominated delta deposition. The Strunian-Visean contact is a minor angular unconformity. The basal part of the Carboniferous (Tournaisian and earliest Visean) is missing. Strunian and Visean quartz sandstones are known only from the northwestern and northern portions of the Berkine Basin (Figure 15). Their present-day distribution is controlled on the north and west by truncation on the Hercynian Unconformity. Nykjaer (1997, personal communication) favors an easterly shale out for the Strunian sandstone packages (Figure 15). Visean deltaic quartz sandstone packages appear to extend along the northern flank of the basin. The quartz sandstones are most likely derived from erosion of older Paleozoic sediments present along the Hassi Messaoud Ridge and Dahar Dome to the west and north (Nykjaer, 1997, personal communication).

Triassic reservoirs, in particular Carnian-aged Trias Argilo Greseux Inferieur (T.A.G.I.) quartz sandstones, are major producers of oil and gas along the western and northern flanks of the Berkine Basin. El Borma Field (Figure 3), discovered in 1964 and extended into Algeria in 1969, was the first significant discovery in the Berkine portion of the Ghadames Basin. Production at El Borma is from T.A.G.I. quartz sandstones. Exploratory drilling during the 1990's resulted in a number of significant Berkine Basin discoveries. Beginning in the middle 1990's (Daniels et al, 1994), these producing reservoirs have been the subject of numerous studies (Drumheller et al, 1997; Ford and Scott, 1997; Scott et al, 1997; Boote et al, 1998; Echikh, 1998; Pink et al, 1999; Scott and Wheller, 1999; and Wheller et al, 1999). Deposition of the T.A.G.I. occurred in an overall transgressive episode during Late Triassic. T.A.G.I. siliciclastic-dominated strata were deposited on a major, low relief, regional erosion surface, the Hercynian Unconformity, which represents an erosion sequence boundary. Drainage throughout most of the T.A.G.I. was focused towards the east and northeast (towards the developing proto-Tethys), in dominantly fluvio-eolian associations, but with widespread lacustrine/marginal

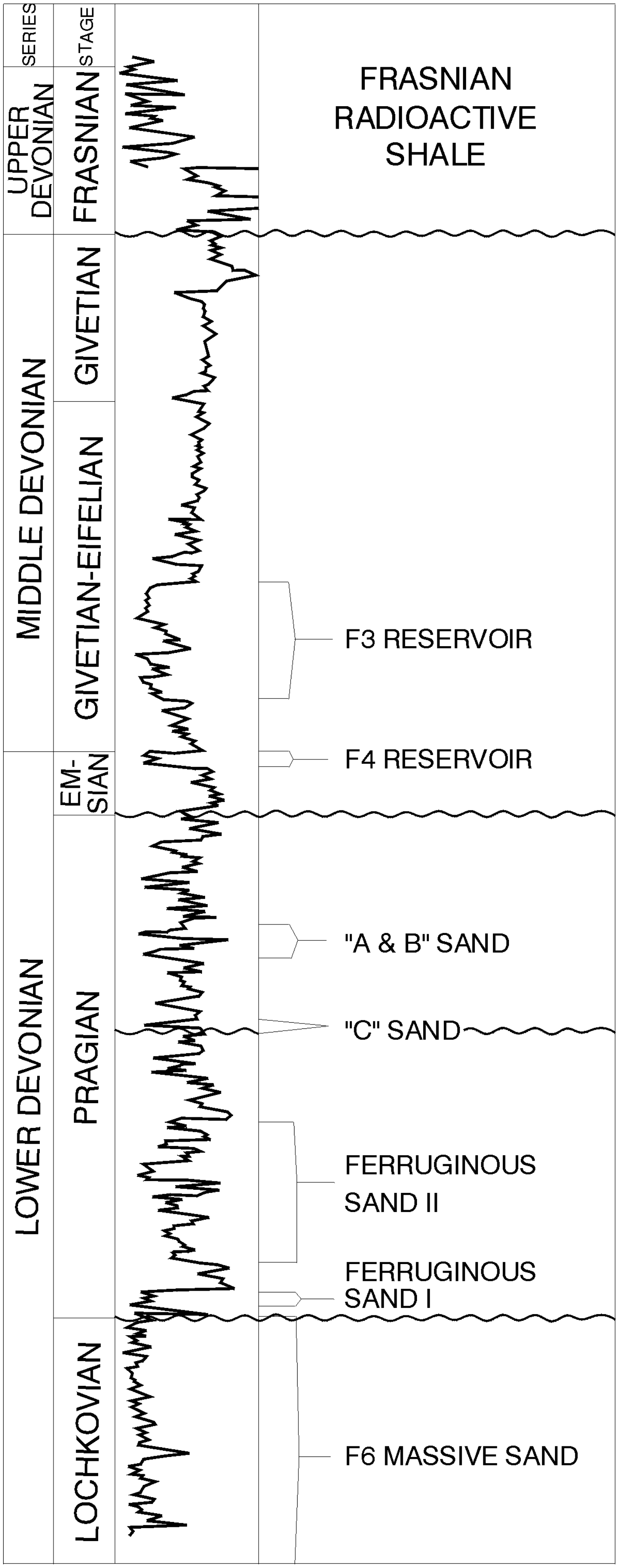

Figure 10

Figure 10. Gamma ray log signature illustrating Lower and Middle Devonian quartz sandstones packages within the Berkine Basin. Data from Nykjaer, (1998, personal communication).

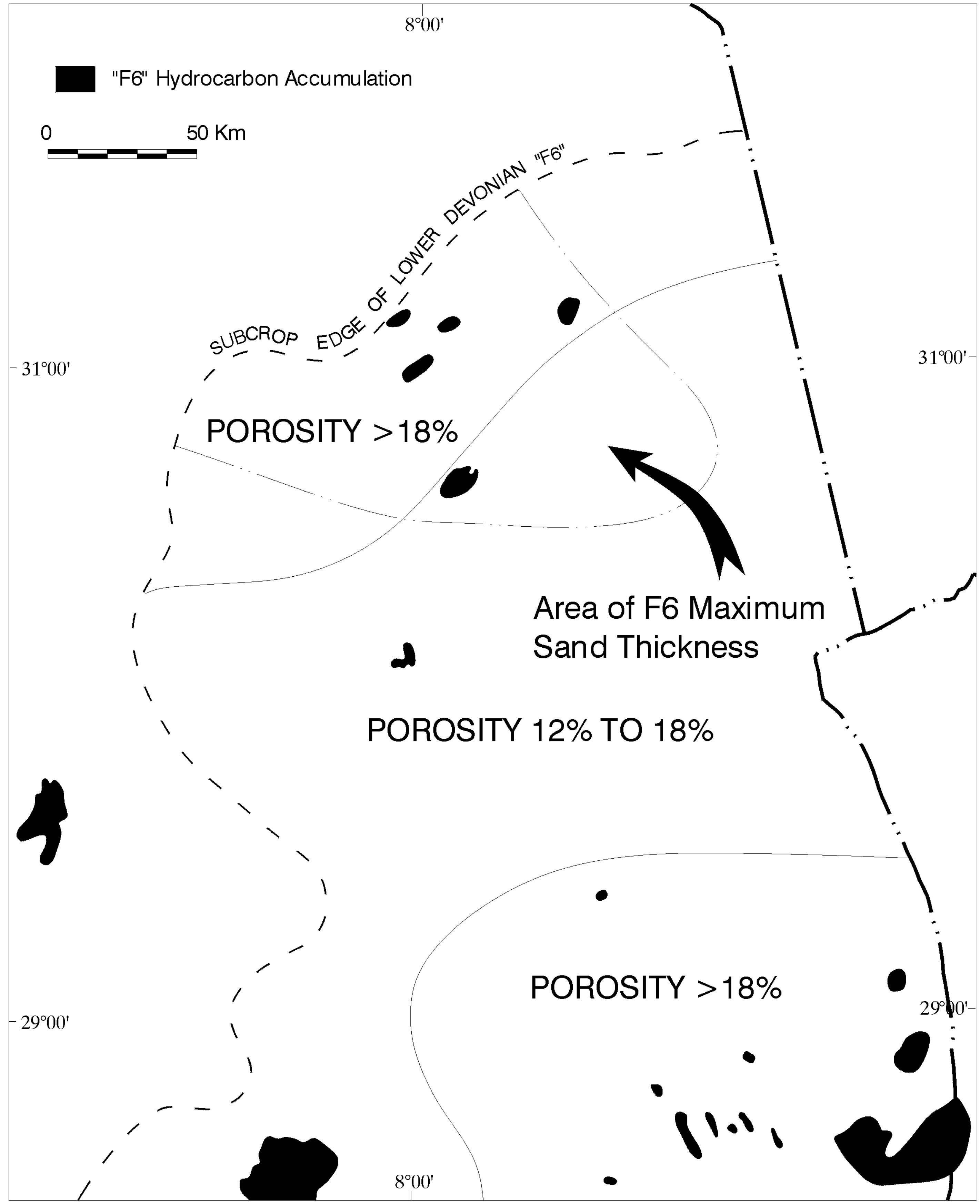

Figure 11

Figure 11. **Generalized porosity distribution and area of maximum quartz sandstone thickness of Lower Devonian (Lochkovian-Pragian) "F6" sandstone interval. Porosity distribution from Sonatrach, 1995. Area of maximum "F6" quartz sandstone thickness from Nykjaer (1998, personal communication).**

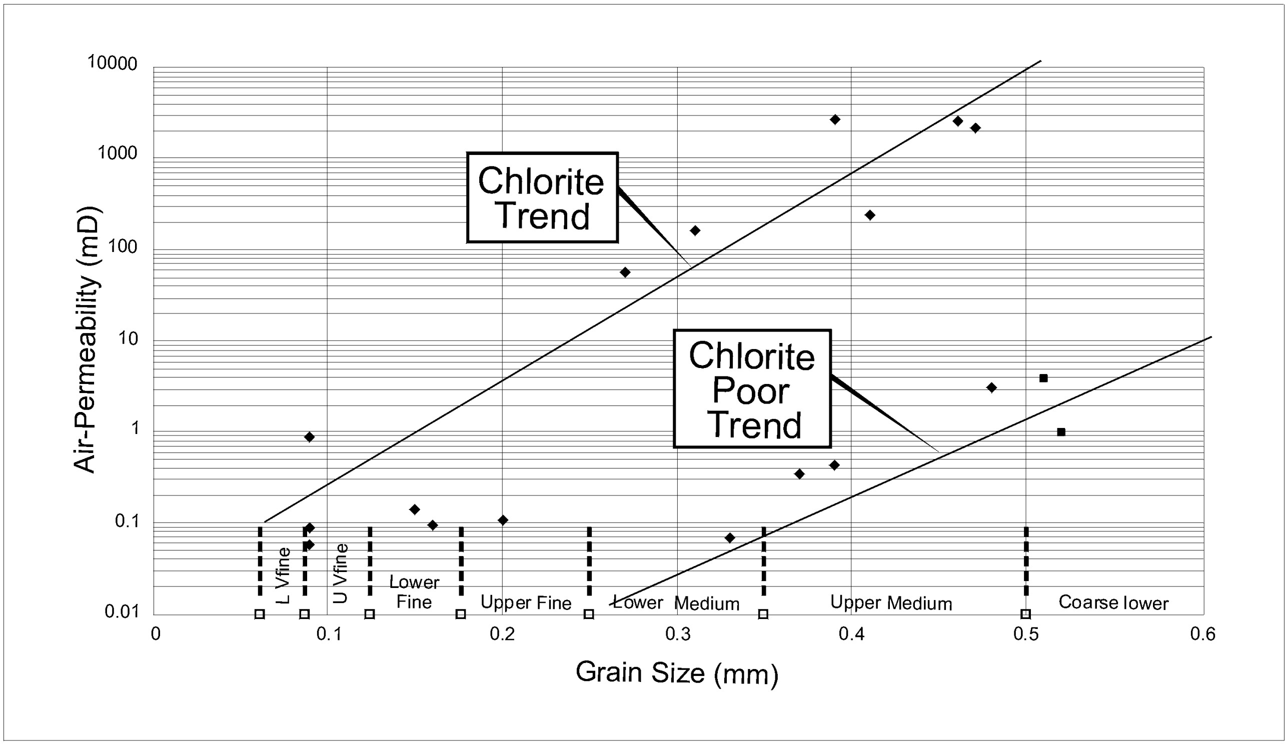

Figure 12. Grain size (mm) versus air-permeability (md) plot for Chlorite and non-Chlorite cemented "F6" (Lochkovian-Pragian) quartz sandstones. Permeability in chlorite and non-chlorite cemented trends typically increases with grain size. Data from Nykjaer (1998, personal communication).

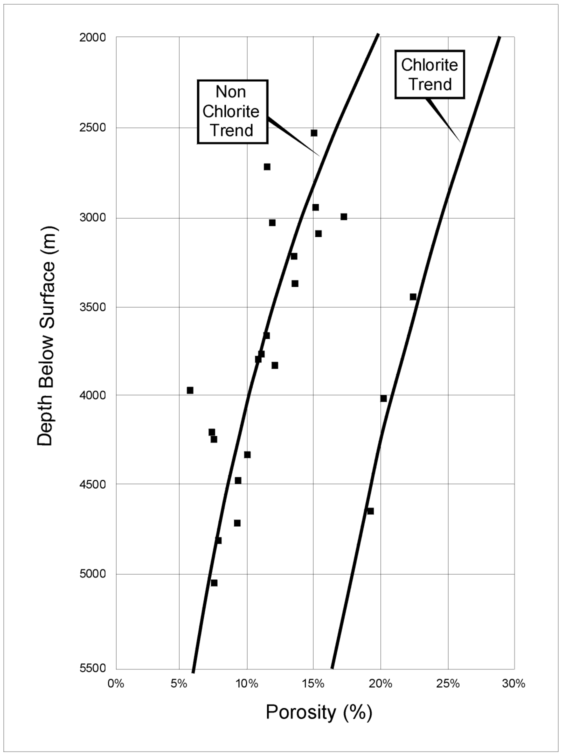

Figure 13. Porosity (%) versus depth below surface (meters) for chlorite and non-chlorite cemented "F6" (Lochkovian-Pragian) quartz sandstones. Chlorite-cemented "F6" quartz sandstones illustrate higher porosity preservation at depth than non-chlorite cemented "F6" quartz sandstones. Data from Nykjaer (1998, personal communication).

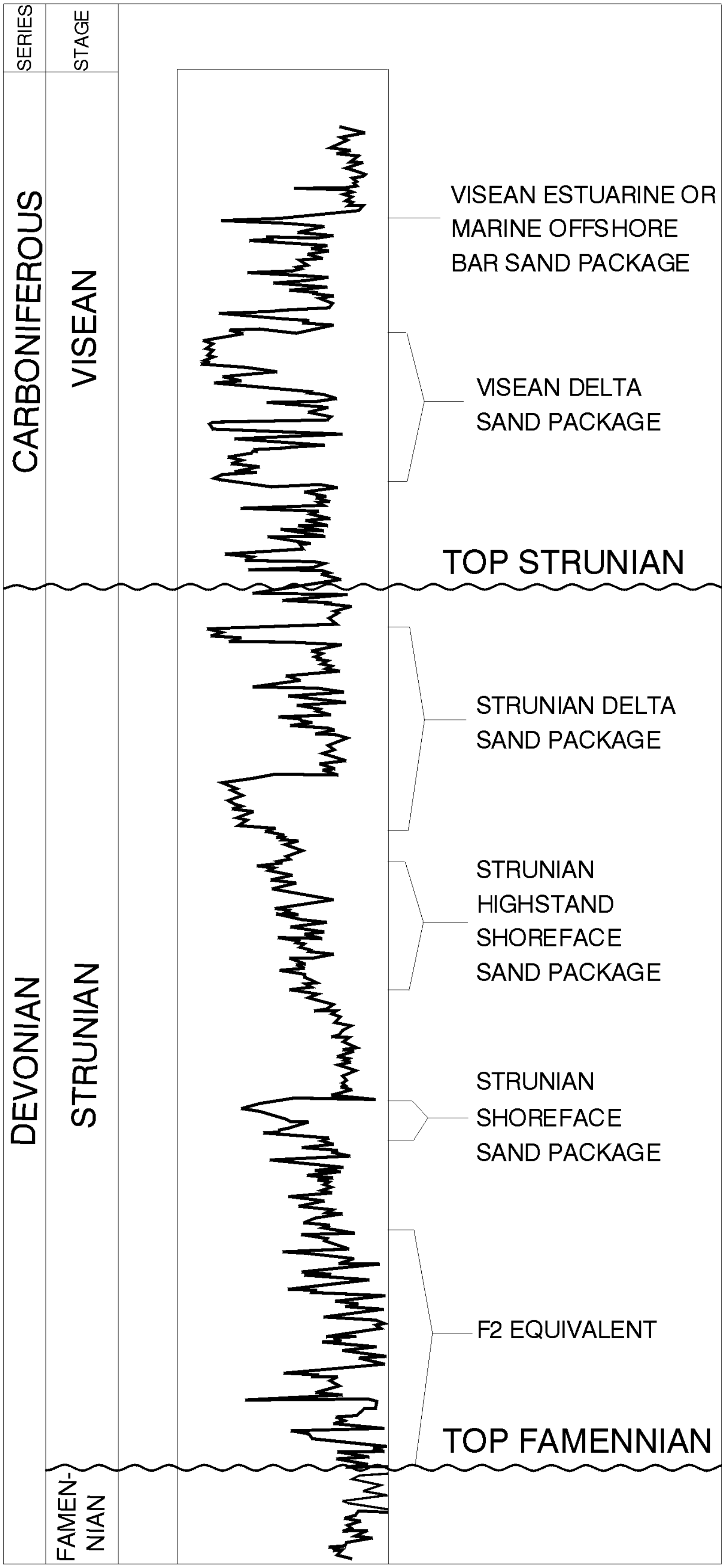

Figure 14. Gamma ray log signature illustrating Strunian (uppermost Devonian) and Visean (Lower Carboniferous) quartz sandstone packages within Berkine Basin. Data from Nykjaer (1997, personal communication).

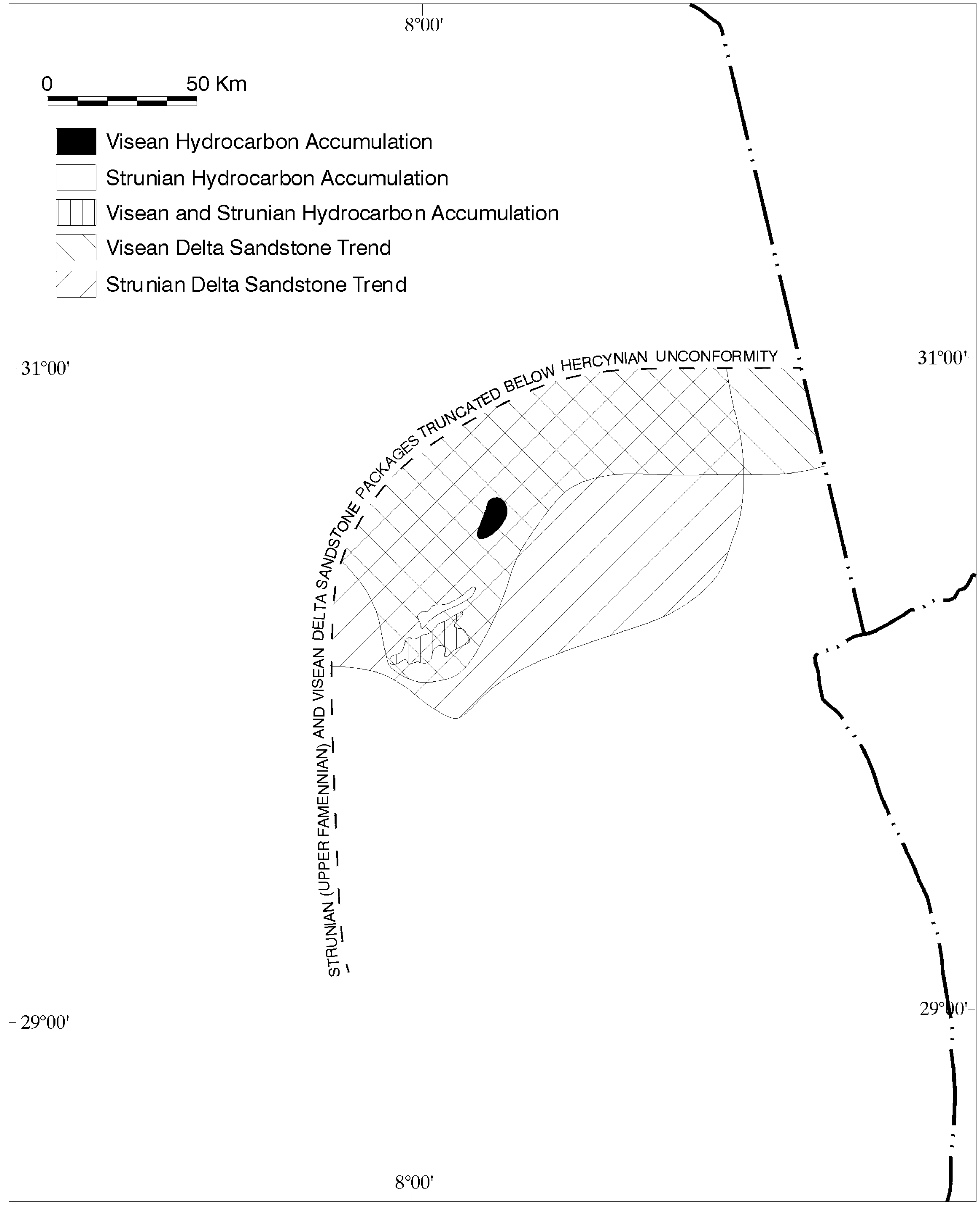

Figure 15. Generalized distribution of Strunian (uppermost Devonian) and Visean (Lower Carboniferous) delta quartz sandstone packages and relation to truncation of Strunian and Visean intervals by Hercynian Unconformity. Data from Nykjaer (1997, personal communication).

sabkha incursions. Late T.A.G.I. deposition followed a trend that became predominant in the overlying Carbonate towards the north and west, with deposition ranging from fluvio-eolian to lacustrine to full sabkha conditions in the north. Few wells have penetrated the area of maximum T.A.G.I. gross sand development (Figure 16) and the depositional relationship of this area to the El Merk-El Borma producing trend is unclear. The T.A.G.I. can be divided into three distinctive sandstone/mudstone cycles (Figure 17) which represent progressive filling of a pre-T.A.G.I. incised valley system (Scott et al, 1997). The majority of T.A.G.I. reservoirs were deposited as fluvial valley-fill and braid plain quartz sandstones and eolian quartz sandstones. Overlying and interbedded with the quartz sandstones are pedogenic carbonate mudstones and sabkha and chott facies (Scott and Ford, 1996, personal communication).

Wilson (1996, personal communication) attributes the excellent reservoir quality of the T.A.G.I. (average porosity of 17% and average permeability of 598 millidarcies) along the northwest portion of the basin to a combination of factors including: (1) Sourcing of T.A.G.I quartz sandstones from a moderately to highly quartzose source terrain. This has resulted in T.A.G.I. sandstones having a high quartz and low feldspathic and lithic content, (2) Moderate to highly saline formation waters present in the T.A.G.I. during most of its burial history, resulting in the lack of alteration of feldspar to clays, (3) Depositional environments which have favored formation of detrital clay rims on framework grains, and (4) Low burial temperatures which prohibited illitization of feldspars and kaolinite. Variation in reservoir quality is primarily associated with grain size. Medium- to coarse-grained quartz sandstones exhibit permeabilities in excess of 3000 millidarcies (Figure 18). Very fine-grained quartz sandstones typically have permeabilities less than 50 millidarcies. Based on detailed petrographic work, Wilson (1996, personal communication) suggests lower T.A.G.I. quartz sandstones within the northwest portion of the basin were derived from erosion of slightly metamorphosed quartzose sandstones. Upper T.A.G.I. quartz sandstones probably were derived from granitic plutons. Lower and Upper T.A.G.I. sandstones may represent a continuum of unroofing of a single source area. Provenance studies for other portions of the T.A.G.I. depositional system are underway.

The youngest producing interval within the Berkine Basin is the Triassic Argilo Greseux Superieur (T.A.G.S.). Where present, T.A.G.S. quartz sandstones overlie the T. A. G. I. reservoirs (Figure 17) and are part of a complex sequence of deposition referred to as the Triassic Carbonate. T.A.G.S. productive reservoirs occur primarily to the west and northwest of the Berkine Basin on the Hassi Messaoud Ridge and within the “Triassic” Basin (Figure 1). Carbonate quartz sandstones are productive within the western portion of the Berkine Basin at EMK and Rhourde El Krouf (Sonatrach, 1995; Mountford, 1999, personal communication). Carbonate quartz sandstones are similar in composition to those of the T.A.G.I. Plagioclase, a very minor component of the T.A.G.I., is present in minor to moderate amounts within the Carbonate sandstones in the Berkine Basin. Based on amounts of feldspar and monocrystalline quartz in the Carbonate sandstones, Wilson (1996, personal communication) suggests they were derived from a different source terrane than the T.A.G.I., probably an adamellite or granodiorite. This may represent continued unroofing of the same source area as that from which the T.A.G.I. quartz sandstones were derived (Wilson, 1996, personal communication).

Hydrocarbon Trapping Styles and Seals

With the exception of BBR Field, hydrocarbon accumulations discovered within the Berkine Basin have been associated with structural traps. Although there is a significant stratigraphic component associated with these structural traps, most discovered Berkine Basin accumulations appear to be associated with upthrown and downthrown faulted blocks in which primary fault movement is Carbonate (Late Triassic) in age. Structural relief of many of the accumulations are expressed as broad, low-relief anticlines complicated by series of horsts and grabens. Many of the faults associated with these structural traps terminate within the Liassic (Figures 19 and 20). In several fields, however, faulting extends into the Cretaceous, suggesting trap modification by Early Cretaceous (Austrian) and possibly latest Eocene (Pyrenean) structural movement.

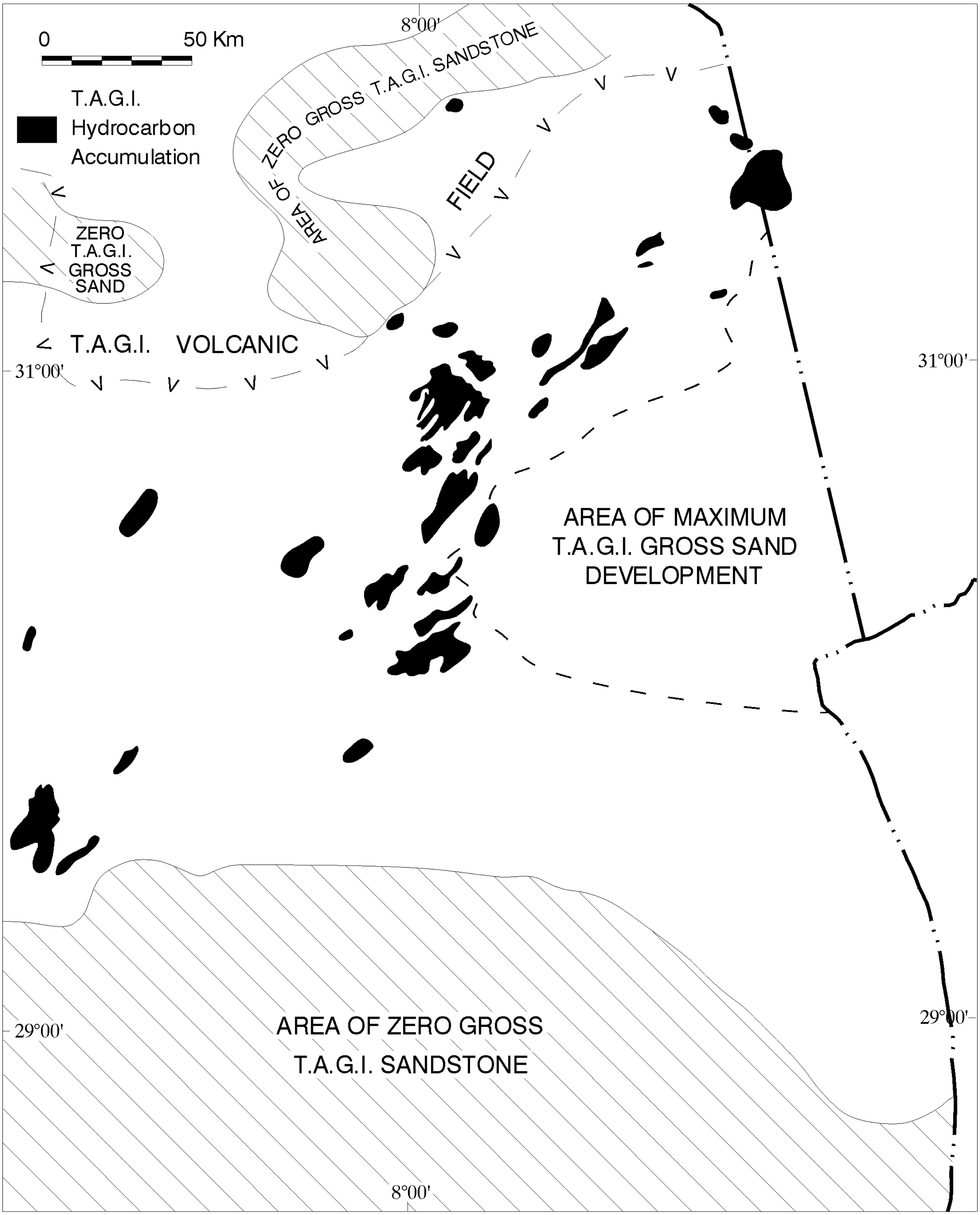

Figure 16

Figure 16. Generalized distribution of Trias Argilo-Greseux Inferieur (T.A.G.I.) quartz sandstone and hydrocarbon accumulations. Data from Mountford (1999, personal communication).

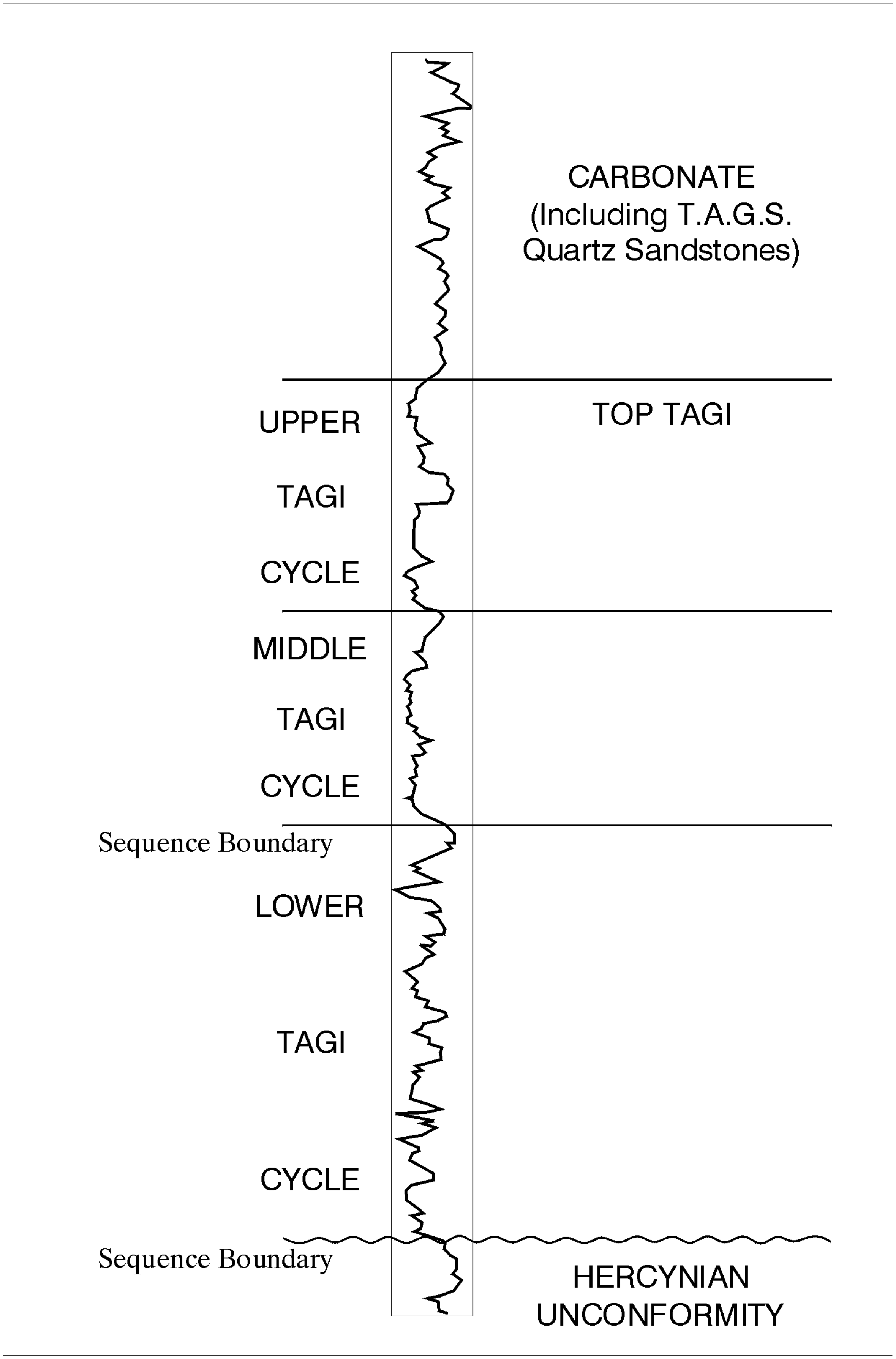

Figure 17

Figure 17. Gamma ray log signature illustrating tripartite sub-division of Trias Argilo-Greseux Inferieur (T.A.G.I.) and overlying Carbonate/T.A.G.S. section. Data from Scott and Ford (1996, personal communication).

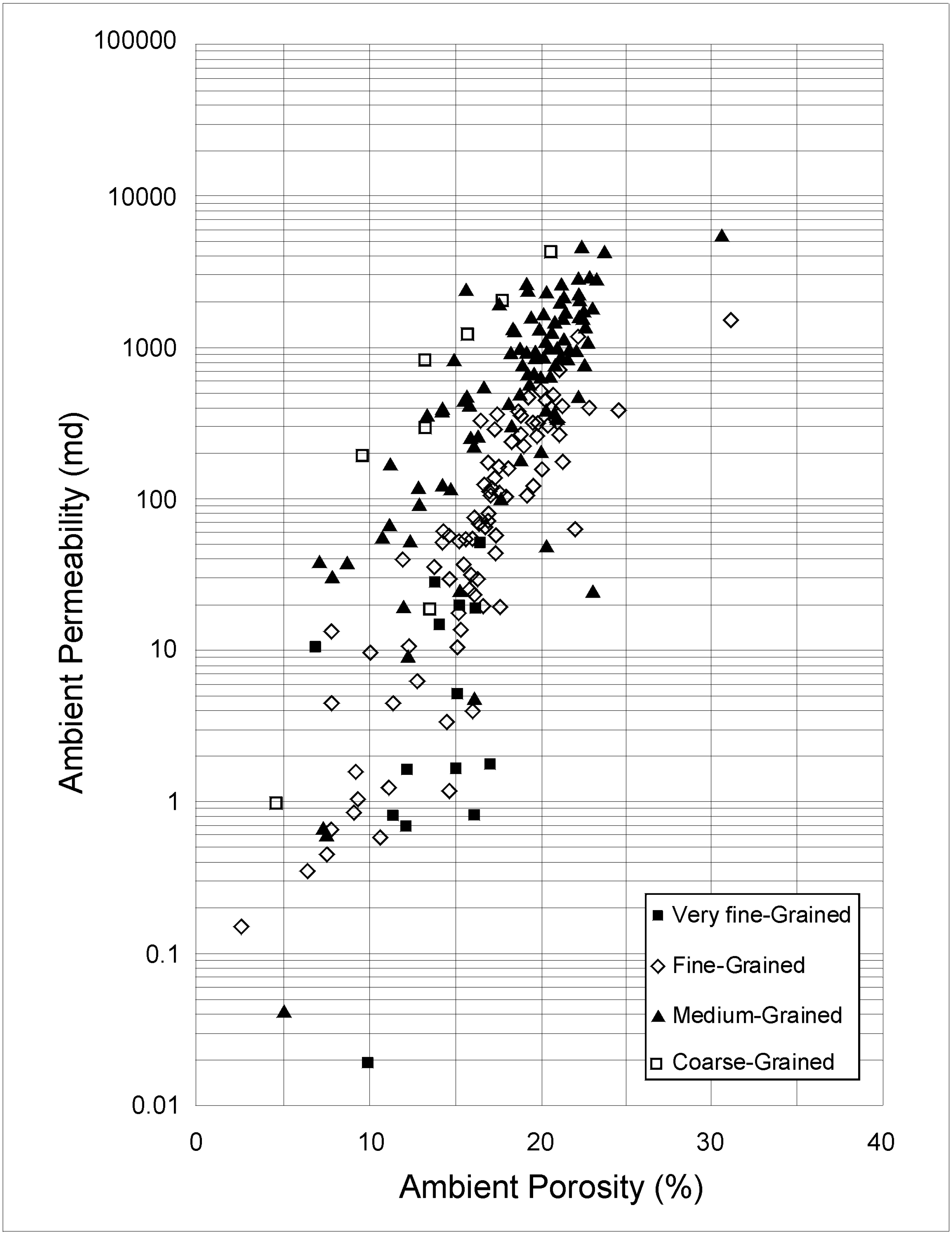

Figure 18

Figure 18. Porosity (%) versus Permeability (millidarcies) plot of Trias Argilo-Greseux Inferieur (T.A.G.I.) quartz sandstones. More coarse-grained quartz sandstones typically have higher porosity and permeability. Data from Wilson (1996, personal communication).

Figure 19. Seismic cross-sections illustrating common types of structural traps within Berkine Basin. Note variability of faults with respect to horizons they cut. Most faults do not cut the Liassic salt section.

Figure 20. Seismic cross-sections illustrating common types of structural traps within Berkine Basin. Note thickening across fault zone in the S4 to Liassic Anhydrites on upper seismic section. Several faults on lower seismic section extend up to Aptian carbonate section.

Subcrop (truncation), stratigraphic onlap or updip pinchout, and hydrodynamic hydrocarbon-bearing traps have been reported from the Illizi Basin (Chiarelli, 1978; Sonatrach, 1995; Echikh, 1998, and Alem etal, 1998) but have yet to be explored for in the Berkine Basin. Considering the stratigraphic complexities of the Devonian, Carboniferous, and Triassic, subcrop and stratigraphic onlap traps should be expected to occur on the flanks of the Berkine Basin and within the T.A.G.I. depositional system. Ford and Muller (1995) suggest the southern flank of the Berkine Basin could hold significant Silurian- and Devonian-reservoired hydrocarbon accumulations associated with pre-Frasnian truncation of quartz sandstone packages across the Mole D'Ahara. Initial exploratory drilling has yet to confirm this model. Based on Chiarelli's (1978) hydrodynamic studies of the southeastern Algeria, hydrodynamic trapping is not considered to be a viable trap type within the Berkine Basin. Although stratigraphic traps have not been directly explored for, the Anadarko group database allows for recognition of significant stratigraphic complexity at all levels, even within the T.A.G.I. depositional system.

The amount of fine-grained siliciclastics in the Devonian, Carboniferous, and Triassic provide for many excellent local hydrocarbon seals which play a significant role in the structural trapping of hydrocarbons. In addition, Sonatrach (1995) identifies four stratigraphic intervals which probably form regional migration seals. These include: (1) Early Silurian (Llandovery) radioactive shales which form the cap rock for Upper Ordovician reservoirs within the Illizi Basin, (2) Late Devonian (Frasnian) radioactive shales, (3) Carboniferous shales which in areas of maximum development within the Berkine Basin impede hydrocarbon migration from Llandovery and Frasnian source rocks, and (4) Triassic and Liassic (Early Jurassic) evaporites which act as highly effective "super" seals. The Triassic /Liassic evaporites act as the roof seal for the overall Berkine Basin petroleum system. Where present, no hydrocarbon accumulations have been discovered nor hydrocarbon shows observed above the Triassic/Liassic evaporite section.

Hydrocarbon Migration and Timing of Trap Fill

Daniels and Emme (1995), Rudkiewicz et al (1997), and Echikh (1998) have demonstrated the complex nature of hydrocarbon migration within the normally-pressured Berkine Basin. Based on paleo-reconstructions integrated with kinetic simulations and fluid-flow modeling, three primary migration paths account for distribution of oil and gas in the Berkine Basin. These include: (1) Updip migration of hydrocarbons in source rock-adjacent reservoir couplets of Frasnian and Llandovery radioactive shales, (2) Vertically up faults which have lower capillary entry pressures than adjacent shales and into reservoirs, and (3) Long distance migration associated with movement of hydrocarbons from the deepest portions of the Berkine Basin in a west and north direction to a position where permeable basal Triassic siliciclastics are juxtaposed at Llandovery and Frasnian subcrop edges. Migration continues updip into Triassic reservoirs associated with the Hercynian Unconformity surface. Daniels and Emme (1995) and Echikh (1998) provide diagrammatic cross sections across the Berkine Basin which illustrate the general nature of these migration pathways. Updip migration in source-reservoir couplets and vertical migration up faults best explain the distribution of oil and gas accumulations within the Devonian and Carboniferous of the Berkine Basin. Distribution of T.A.G.I. oil and gas accumulations fit long-distance migration pathway models.

Modelling of Llandovery radioactive shales timing of peak oil generation by Daniels and Emme (1995) demonstrates many of Silurian sourced oil-filled traps, generated during the Paleozoic, have probably been destroyed by Hercynian erosion. Only along the northern and perhaps southern flanks of the Berkine Basin would Paleozoic-formed and oil-filled traps be preserved (Figure 8). Timing of peak oil generation for Frasnian radioactive shales (Figure 9) suggests most present-day trapped oil is sourced from this interval. Present-day trapped oil sourced from Llandovery radioactive shales appears to be restricted to the northern portion of the basin. Modeling of a number of hydrocarbon-charged structural traps indicates post-Hercynian development. Mesozoic and younger structural trap development was favorable for accumulation of Frasnian-sourced oil. Because Llandovery and Frasnian radioactive shales are presently beyond the peak-oil window in the central portion of the Berkine Basin, present-day gas accumulations are probably a product of both Early Silurian and Late Devonian sources.

PRIMARY RISK IN EXPLORATION FOR UNDISCOVERED RESERVES

The presence of multiple, organic carbon rich source rocks, high porosity and permeability reservoirs, effective local and regional hydrocarbon seals and favorable development of traps of a sufficient size to accumulate large quantities of oil and gas within the Berkine Basin lead us to conclude the primary risk in exploration for additional hydrocarbon reserves is successful seismic imaging of reservoirs and traps. Although Vibroseis acquisition and state-of-the-art processing has partially resolved a number of general imaging problems, seismic resolution of hydrocarbon-bearing reservoirs needs to be improved. Down-hole multiples associated with Mesozoic evaporites and carbonates still provide some uncertainty with respect to proper imaging of structural traps. Use of 3D seismic in association with development of discovered fields has greatly aided in resolution of fault geometries and subtle nature of the structural traps. Accurate mapping of the Late Triassic-Early Jurassic (Liassic) interval is necessary with respect to growth history of faulting typically associated with structural traps. Further work with respect to proper bin size needs to be done for adequate resolution of faults.

Figure 21 illustrates the stratigraphic position of seismic horizons which can be correlated and mapped with varying degrees of confidence throughout the Berkine Basin. The Hercynian Unconformity surface, an important surface in prediction of T.A.G.I. reservoir distribution and critical to identification of potential subcrop traps, is not a consistent reflector. It’s seismic resolution is directly related to underlying Paleozoic lithology and fluid contents and is area dependent. The primary oil-charged reservoir (T.A.G.I.) is presently not seismically resolvable. Imaging of Devonian and Carboniferous reservoir intervals awaits further developments with respect to optimum fold, receiver array, and offset studies. If exploration for non-structural traps within the Berkine Basin is to become efficient, imaging at the reservoir interval level needs to be resolved.

BERKINE BASIN UNDISCOVERED HYDROCARBON RESOURCE

Based on Daniels and Emme’s (1995) calculations of generated hydrocarbons from Llandovery and Frasnian radioactive shales, Macgregor (1998) estimates generated petroleum within the Berkine and Illizi Basins is more than two orders of magnitude greater than filling of discovered traps. With most of the proven reserves being concentrated in the Illizi Basin, and considering quality and thickness of Llandovery and Frasnian source rocks within the Berkine Basin (Daniels and Emme, 1995), Macgregor (1998) concludes the Berkine Basin is immature with respect to discovered hydrocarbon reserves and suggests significant yet-to-be-discovered fields in the 250 to 800 MMBOE range are feasible.

Considering the maturation histories for Llandovery and Frasnian source rocks and timing of peak oil generation, we anticipate a significant portion of the undiscovered hydrocarbon resource in the Berkine Basin will be in the form of gas and condensate, particularly with respect to exploration for Paleozoic reservoirs. Successful exploration for Late Triassic (T.A.G.I., T.A.G.S., and Carbonate) accumulations will continue to be a primary contributor to future oil reserves.

Exploration within the Berkine Basin is still in the structural trap phase of its life cycle and additional structural traps will continue to be discovered. Various Paleozoic intervals truncated by the Hercynian Unconformity along the western and northern portions of the basin should yield significant subcrop traps provided seismic imaging problems associated with the Hercynian surface can be resolved. Distribution of Visean and Strunian reservoir trends in the northern portion of the basin suggest stratigraphic onlap/updip pinchout traps will be present. The fluvial nature of the El Merk-El Borma T.A.G.I. producing trend should also yield numerous stratigraphic traps.

Important stratigraphic intervals for future exploration of the Berkine Basin include the Lochkovian-Pragian “F6 massive sandstone” interval, Strunian shoreface and delta sandstone packages, Visean delta sandstone packages, and Carnian T.A.G.I. fluvial sandstone packages. Of these intervals, the “F6 massive sandstone” interval is the most widespread (Figure 11), deepest, and most high risk due to porosity versus depth relationships. Visean and

Strunian exploration will be the most geographically restricted (Figure 15). The northeast trending T.A.G.I. depositional system (Figure 16) is the most well understood stratigraphic interval within the Berkine Basin and will continue to yield future discoveries. The relationship of this depositional system to additional T.A.G.I. depositional systems on the western flank of the basin and in the area of maximum sand development needs to be clarified. Pre-Lochkovian hydrocarbon potential of the Berkine Basin is unknown. Insufficient penetrations of Lower Silurian, Ordovician, and Cambrian intervals preclude any discussion of their hydrocarbon potential. Based on maturity mapping of known source rock intervals, hydrocarbon-charged reservoirs in these stratigraphic intervals will necessarily be dry gas.

Figure 21. Stratigraphic position of seismic horizons which can be correlated and mapped with varying degrees of confidence throughout the Berkine Basin.

CONCLUSIONS

The Berkine Basin petroleum system compares favorably to other world class petroleum systems. Multiple major hydrocarbon source rocks of Early Silurian and Late Devonian age are rich in total organic carbon content (2 to >17%) and have a generation and expulsion history which coincides with development of structural traps of a sufficient size to accumulate giant accumulations of oil and gas. Early Devonian through Late Triassic reservoirs are high porosity (up to 20%) and permeable (in excess of 1,000 millidarcies) quartz sandstones. Although migration of hydrocarbons is complex, a series of excellent regional shale and evaporite seals effectively contain the hydrocarbons.

The Anadarko group’s exploration history demonstrates the value of understanding the petroleum system. Early exploration was directed towards up-dip portions of the present-day structural basin and failed as a result of inadequate mapping of source rock “kitchens” and understanding of the hydrocarbon migration history. Re-appraisal of the group’s exploration model shifted attention to a position closer to the hydrocarbon “kitchen” where a more complete Paleozoic section was preserved and regional fault systems provided sites for vertical migration and entrapment. Employment of geophysical data as the primary tool for definition of prospects has evolved from reprocessing of 1970’s 12-fold data to acquisition of extensive 120-fold and 240-fold 2D seismic grids and employment of 3D seismic in development of discovered accumulations. Continued refinement of seismic acquisition and processing is needed to effectively image hydrocarbon-bearing reservoirs and efficiently explore for non-structural traps.

The yet-to-be-discovered Berkine Basin hydrocarbon resource is significant. Although large oil accumulations will continue to be discovered within the Late Triassic interval, Paleozoic accumulations will probably be gas and condensate. Yet-to-be-discovered fields up to 1,000 MMBOE are feasible.

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