Sedimentology and Diagenesis of Some Neocomian-Barremian Rocks (Chouf Formation), Southern Lebanon

The Neocomian – Barremian rocks are well exposed in southern Lebanon (Jezzine), yet they were not properly studied to date. The present study involves modern detailed and state of the art petrographic and mineralogical analyses of these rocks. The Chouf Formation was deposited both in fluvio-deltaic (aquatic based systems) and eolian environments (terrigenous systems). Evidence of this is obtained in the field, looking at preserved primary structures (in the Lower parts of the Formation – for the aquatic dominated systems – and in the mid parts of the Formation – for the continentally-dominated systems). Thus, both types of sandstone strata are found involving different environments of deposition with cyclical control. Lithostratigraphic and petrographic analyses revealed that the Homsiyeh outcrops include five distinct facies. Each of them was studied in detail with modern petrographic and x-ray diffraction methods. This petrographic study sheds more light on the characteristics of the organic rich layers in the aquatic dominated facies mainly occurring in the lower part of the Chouf Formation, which generally act as poor reservoirs. The strata mid section of the Chouf Formation, composed mostly of arenites, often act as good reservoirs, due to the low amounts of clays. Several bitumen (or plant kerogen) generated form the aquatic strata were studied in detail. They resulted in corrosion and dissolution of the quartz grains (in the sandstones) increasing the porosity/ permeability of the bulk rocks upon initial hydrocarbon migration and later on the telogenic flushing with meteoric waters. Both the burial history and pyrolisis results point out that the organic matter was improperly matured to produce lignite/ coal beds. The low hydrogen index, (HI), high total organic carbon (TOC) and temperature barely reaching the oil window confirm this.

Introduction

Several studies in the Middle East were undertaken on sandstones of Neocomian-Barremian age. The Heletz/ Gevar Am strata in Israel/ Palestine (Cohen, 1976; and Beydoun, 1995), the Nubian sandstones in the Gulf of Suez (Beydoun, 1995), and the Cheriffe Formation (i.e. Ruthbah) in Syria (Beydoun, 1995; Brew, 2001; and Brew *et al.*, 2001a, b) were studied to assess source and reservoir rock potentials. These Levantine clastic formations were proven to contain hydrocarbon, also show similarities with the Chouf Formation (Neocomian-Barremian) in Lebanon. Figure 1 shows a generalized sketch map of Lebanon with typical sandstone outcrops (refer to Ukla 1970 for isopach data), where the study area is shown in the boxed area. Ukla (1970) demonstrated that the sandstone strata are thickest (250m) beneath the Chouf area, and decrease in thickness northwards (e.g. Hermel) and southwards to reach vales near 0m. The study area is located in Southern Lebanon near the Mohafazat Jezzine. It consists of two sections showing key beds from the basal Cretaceous sandstones (Fig. 2). This sketch map presents the respective locations of both sections near the Homsiyeh village. The first section is located near a house in the Homsiyeh village (N 33º33' 113", E 035º33' 391"). The second one is located on a road-cut section near Aazour (section starts at N 33º33' 006", E 035º32' 966" and ends at N 33º33' 010", E 035º33' 036"). Figure 3 shows the generated stratigraphic log from the study (e.g. Bellos, 2008).

The main objectives of this project include the sedimentological and petrographic studies of representative facies forming the Neocomian-Barremian clastic rocks in the Jezzine area (southern Lebanon), which will help in identifying their petroleum potentials.

Geologic Setting

Lebanon is part of the Palmyrides basin, which extended from the Euphrates River to the Mediterranean (Figs. 2.1, 2.2), following a NNE-SSW trend. Throughout the Mesozoic, the basin acted as a depocenter (Brew *et al.*, 2001a, b). Lebanon is also part of the Levantine margin, which roughly extends from the Mediterranean sea (near Cyprus) until the Nile River delta in Egypt (Fig. 3). The Palmyrides Basin growth was ascribed to listric faults, but was caused by plate-scale folding structures (Ponikarov, 1966, 1967; Chaimov *et al.*, 1992; and Wood, 2001). Rifting prevailed along the margins of the Eastern Mediterranean, resulting in the formation of the Levantine margin, during the Triassic (Stampfli *et al.*, 2001; Walley, 2001).

Eyal (1996) postulated that the present stress field fluctuates between the Syrian Arc fold belt (WNW shortening, NNE extension) and the Dead Sea transform (NNW shortening, ENE extension). Clearly, the main tectonic processes are caused as a result of the movements of the Arabian plate with respect to the Zagros belts, creating a collision margin there (cf. Walley, 1998), which may have been the main cause for the Syrian Arc Deformation which created several changes in facies as a result (e.g. Walley, 1997, 1998). The general tectonic settings are shown in Figure 3 (Walley, 1998, 2001).

Figure 1. *Basal Cretaceous Sandstone (and Lower-Cretaceous strata) outcrop map of Lebanon (Dubertret et al., 1955), showing extrapolated isopach data (Ukla, 1970)*

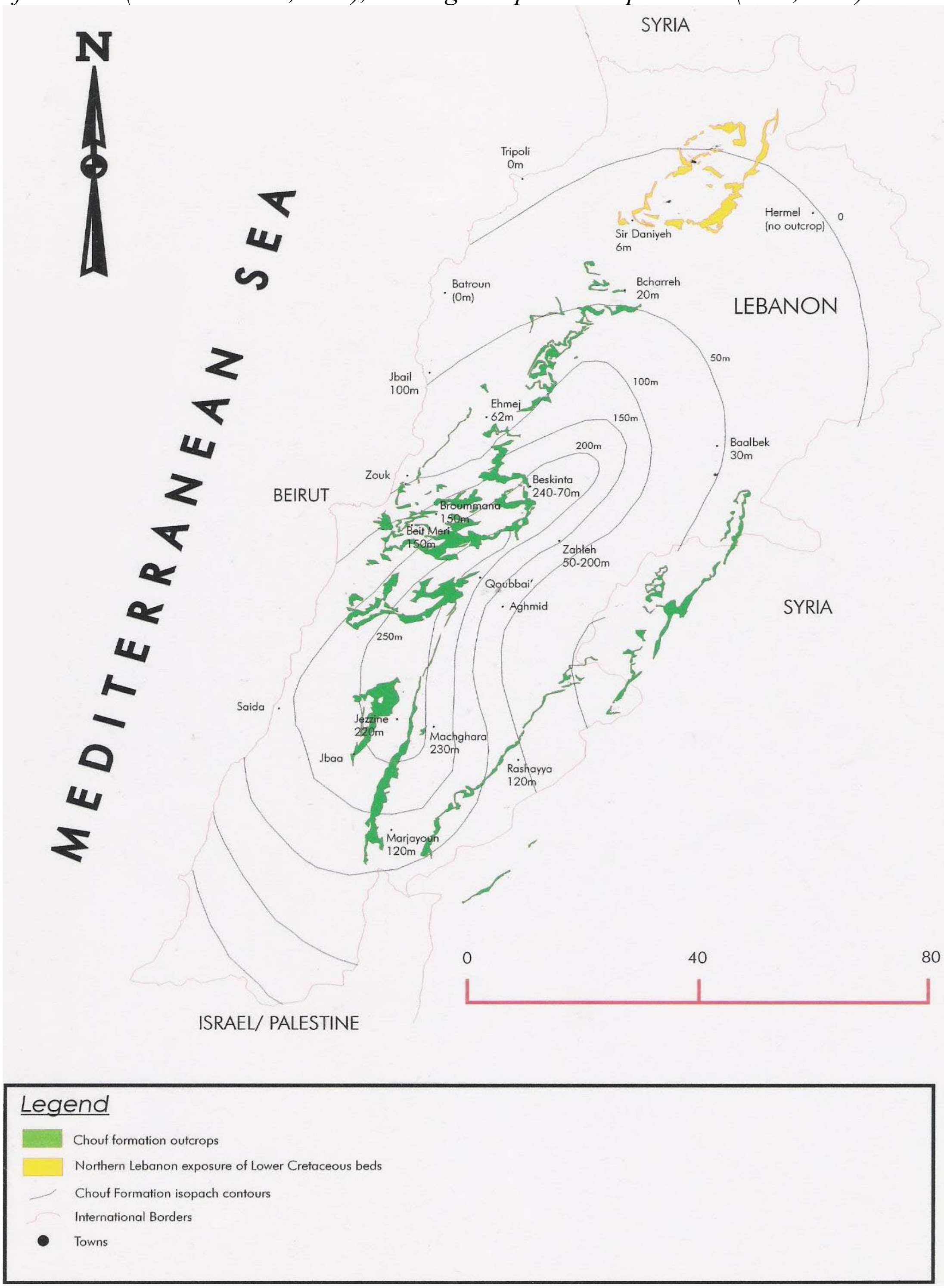


Figure 2. *Geological sketch map of the study area showing the location of both Homsiyeh sections. (F = Fault and, 222, and 223 are the reference numbers (and locations on the index map) for the two air photos used to construct the detailed geologic map. Inset map (cf. Ukla, 1970) with boxed area representing study area. The stratigraphic logs (shown in Fig. 3) were constructed based on actual field work (Bellos, 2008)*

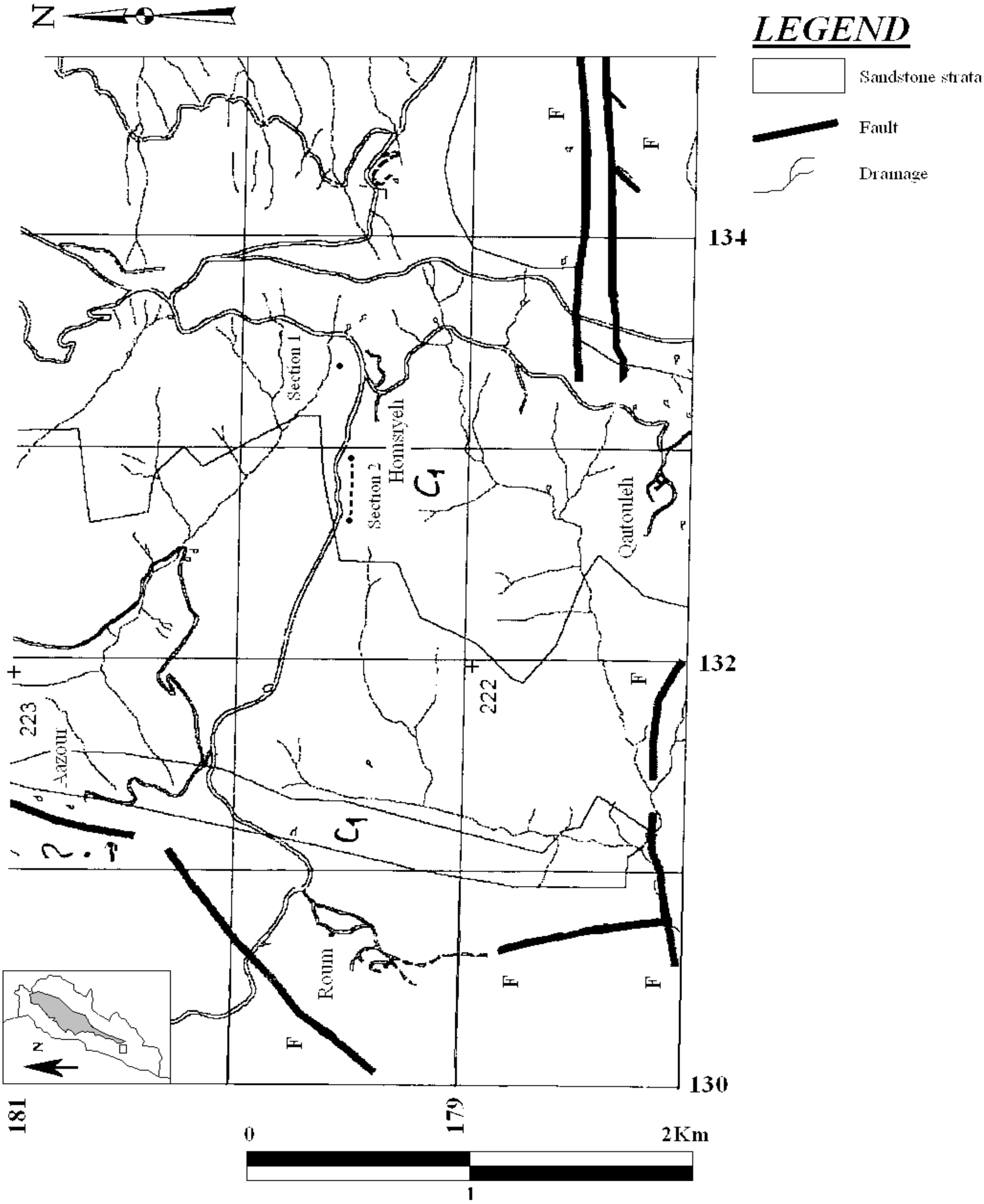
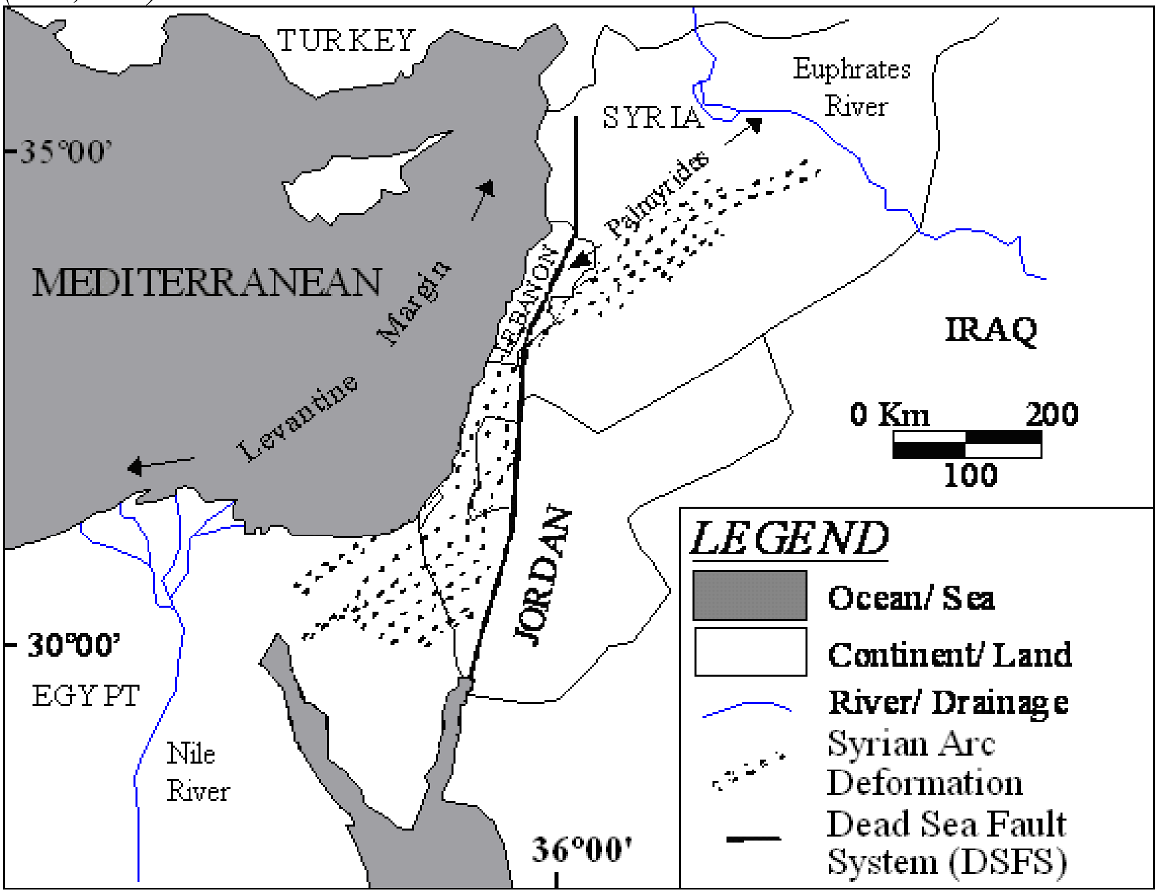


Figure 3. *General sketch map of the Middle East showing the extension of the Levantine Margin and the Palmyrides trend as well as the Syrian Arc Deformation and the Dead-Sea Fault System. Map constructed from data taken from Walley (1998, 2001)*



Methodology

Following reconnaissance and extensive field work visits, several key samples have been analyzed in the laboratory through petrologic (using both by granulometric and microscopic techniques) and x-ray diffraction methods. Granulometric studies are quite important in order to determine the sandstone rock nomenclature, degree of maturity, kinetic energy amount and the depositional settings (Folk, 1968). First the samples are prepared (disaggregated), then they are sieved, and finally the results are interpreted. An example of sieving plots is shown in Figure 4 and, Figure 5 shows an actual example from Toumatt-Jezzine Aazibi.

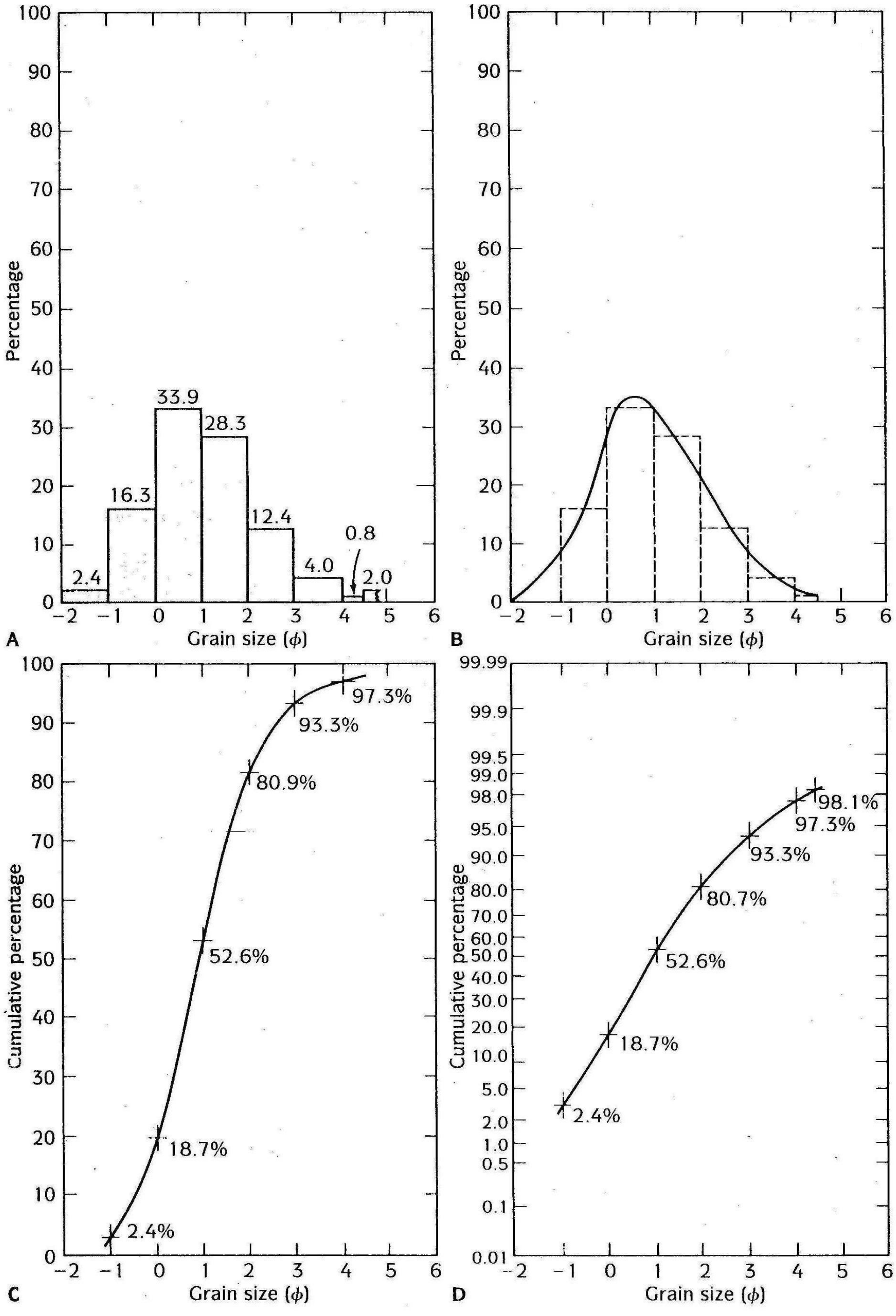


Fig.4

1 Results of a single sieve analysis displayed in various ways. (A) Histogram. (B) Noncumulative size-frequency curve. (C) Cumulative curve on normal graph paper with a standard arithmetic ordinate scale. (D) Cumulative curve on probability graph paper. The ordinate scale collapses the values in the center (the 10%–80% range) and stretches out the values on the tails (less than 10% and greater than 90%), making the curve in (C) into a straight line. On probability paper, therefore, each normal distribution plots as a straight line segment. The phi values can be read directly from these plots and plugged into the formulas shown in Table 5.3 to calculate statistics quickly and easily. (Modified from Blatt, 1992, *Sedimentary Petrology*, 2nd ed., Fig. 16-5, p. 474; by permission of W. H. Freeman, New York.)

Fourty thin-sections were studied both by conventional and cathodoluminescence microscopy; results on limestone is shown in Figure 6, sandstone in Figure 7. Finally, X-ray diffraction methods (XRD) were used to assess bulk mineral composition. An example is shown in Figure 7.

Figure 5. *calculated granulometric data for a generic sandstone sample from the Toumatt-Jezzine Aazibi Section (Machghara section)*

SIEVING DATA (M 3)

Held on:			Raw weight (g)	% Aggregates	Correct weight (g)	Cumulative		Individual %
Mesh	mm	Phi Ø				weight (g)	%	
20	0.84	0.25	2.5	0	2.2	2.2	2.13	2.13
35	0.5	1	7.7	0	7.6	9.8	9.49	7.36
60	0.25	2	24.2	0	24.2	34	32.91	23.43
120	0.125	3	30	0	30.1	64.1	62.05	29.14
200	0.074	3.75	30.4	0	30.4	94.5	91.48	29.43
Pan	<0.074	4	8.8	0	8.8	103.3	100.00	8.52
Total			*103.3*		*103.3*			

Results:

σ_G = 1.14 = "poorly *sorted sand*"

σ_I = 1.05 = "poorly *sorted sand*"

Immature sandstone (Clay = 8.52%)

Figure 5. *Transmitted light photomicrograph (plane polarized light; PPL) of a limestone facies (# H 3.3b, sample 15), from Homsiyeh section 1 (Jezzine). Note the presence of plant roots (Ro)*

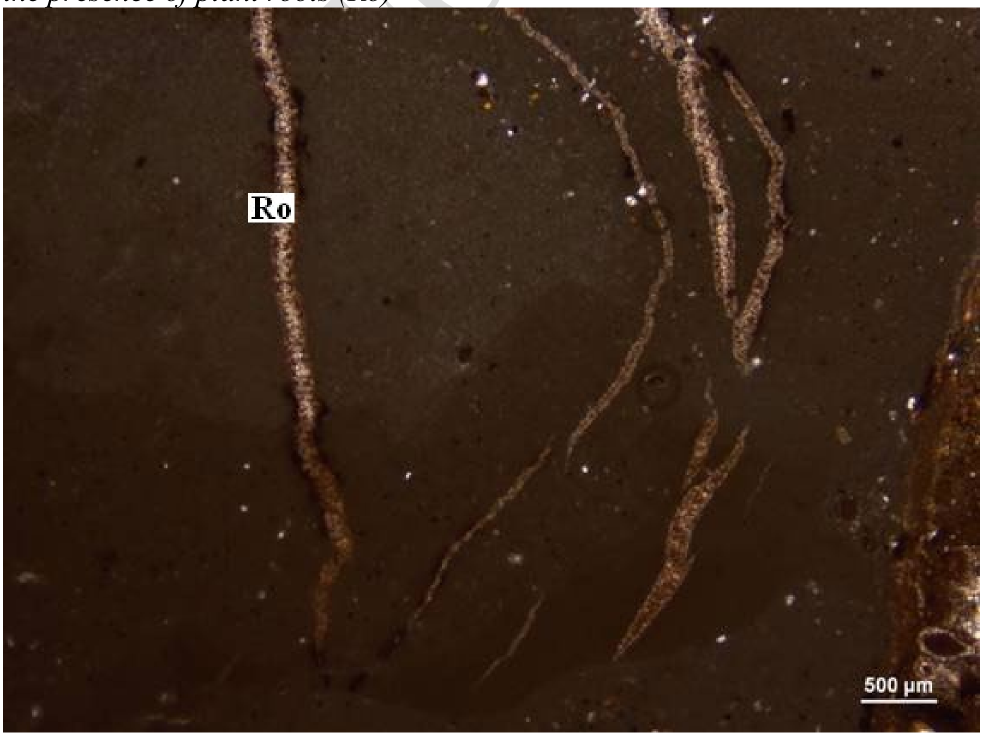
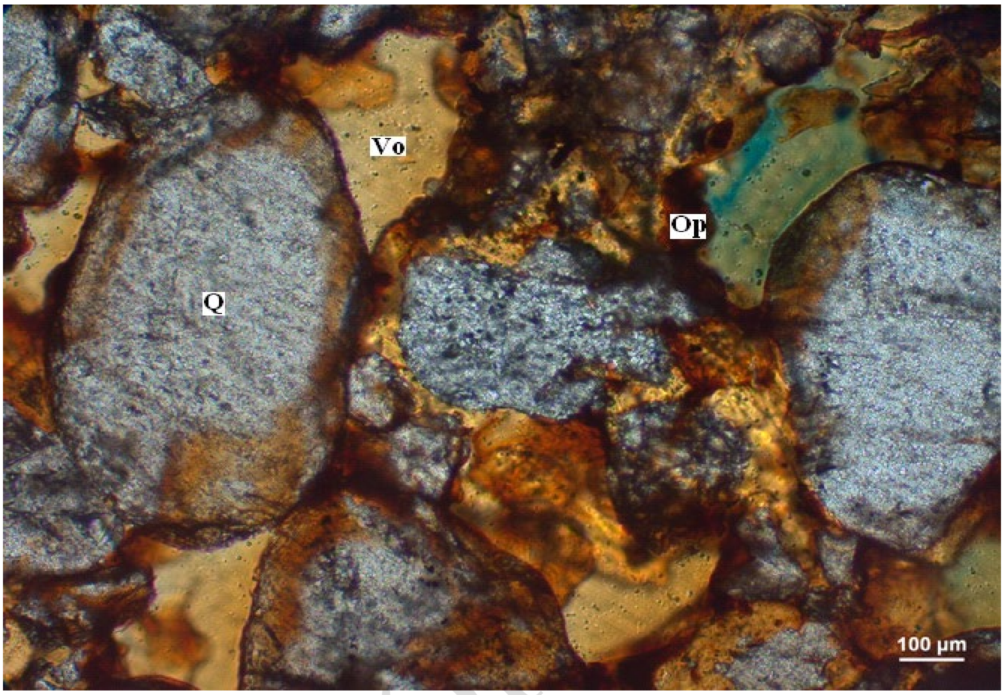


Figure 6. *Transmitted light (PPL; A) and CL (B) photomicrographs of a sandstone facies in the Homsiyeh Section 2 (Jezzine). Note the presence of corroded quartz grains (Q), voids (Vo), and opaque materials (Op; including iron-rich deposits and organic matter) as well as feldspar (Fr) in the center of the CL view. Most strata of this facies (shown later) display similar CL patterns*

A.



B.

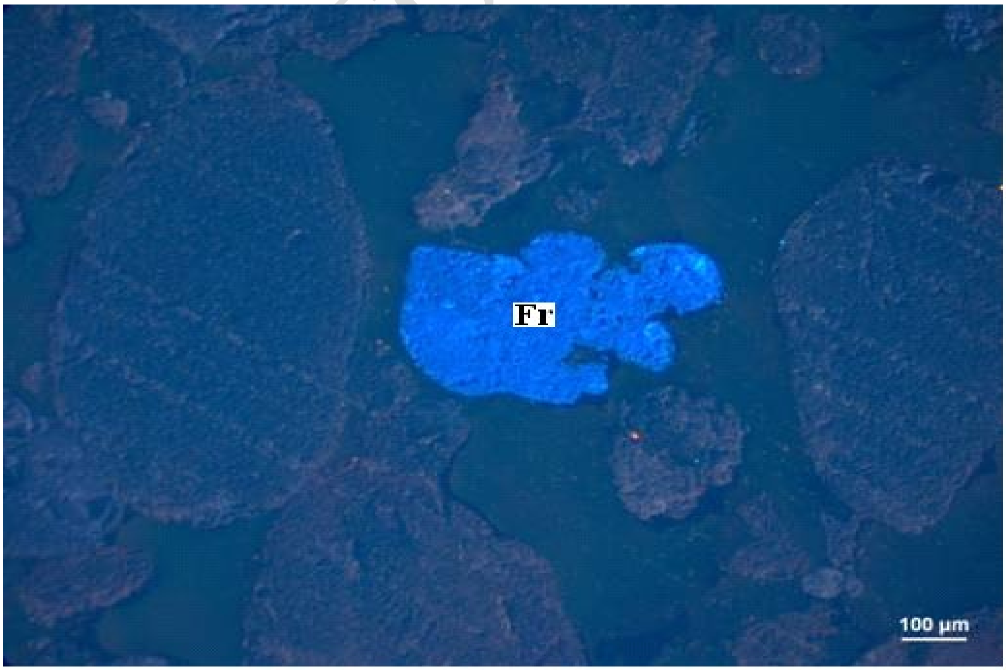
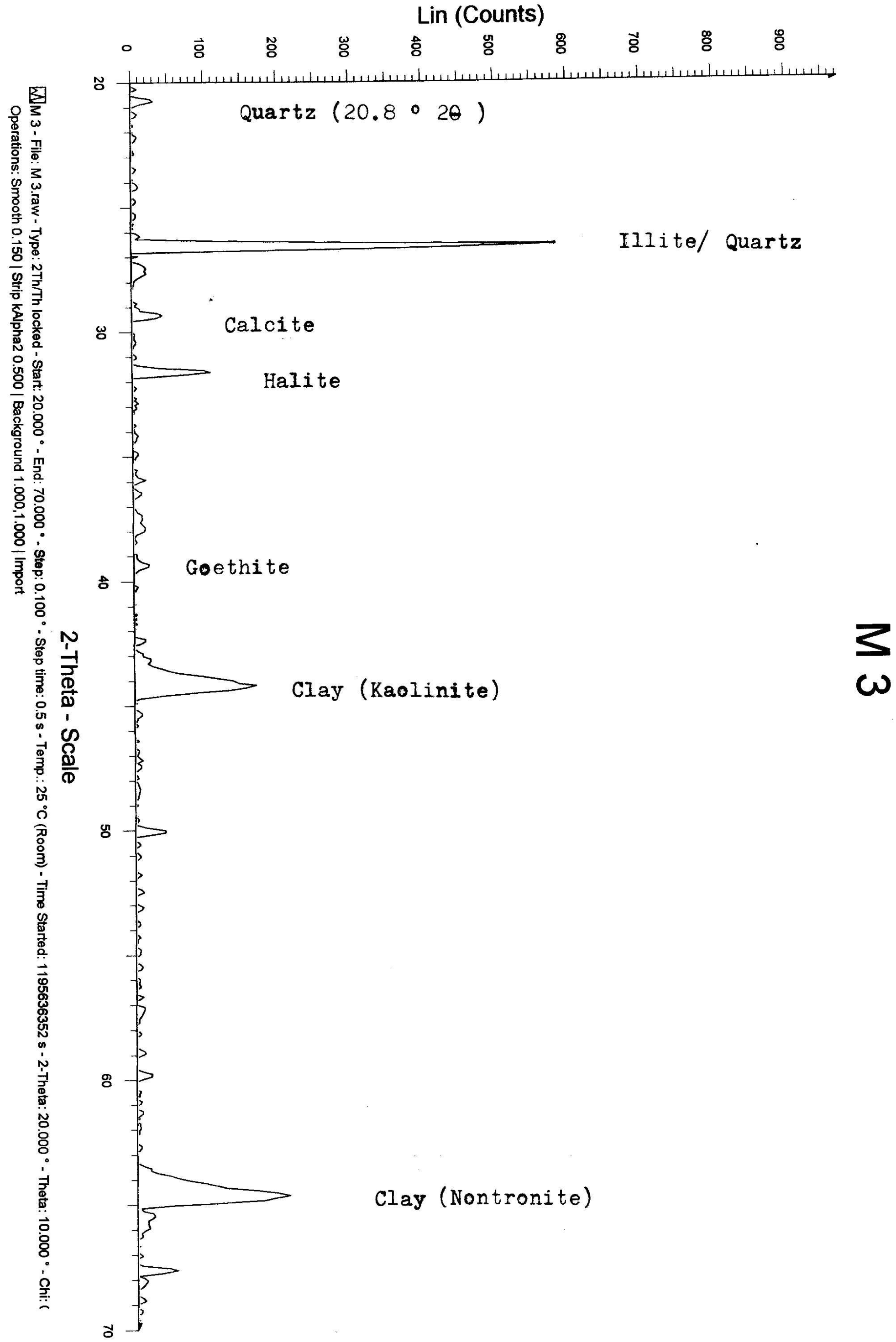


Figure 7. *Uncalibrated X-ray diffractogram showing the mineralogical content of a sandstone facies (# M 3) from the Toumatt-Jezzine/ Aazibi section. Note the presence of quartz (20.8° 2θ), calcite (29.5° 2θ) and clays (45° and 67.5° 2θ). Both identified clays were named. Although this was an immature sandstone bed, most identified strata showed similar XRD patterns*



Fieldwork and Petrology Results

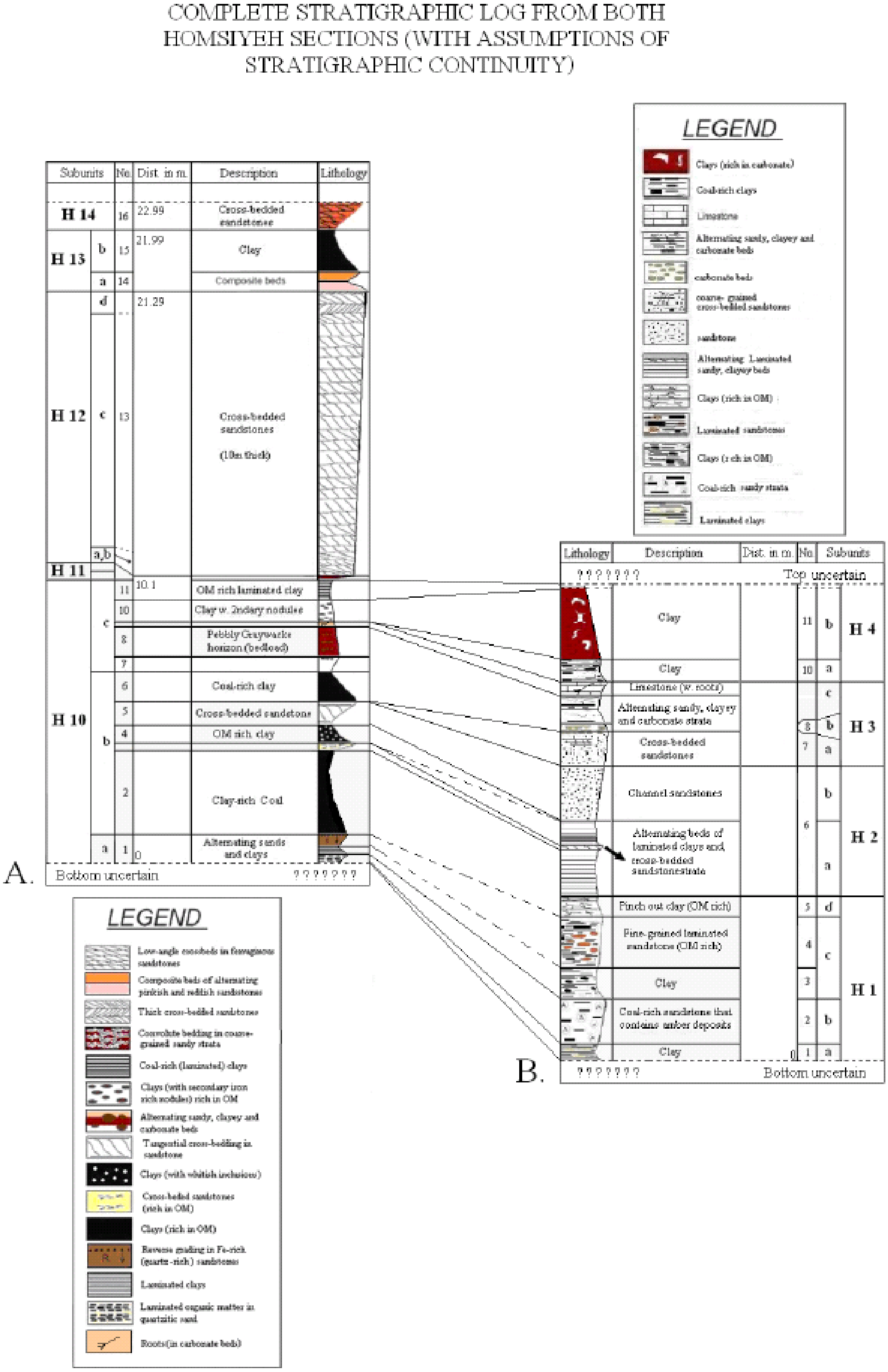
Fieldwork

Table 1 shows the constructed general stratigraphy based on the identified sections of the Homsiyeh area, showing 14 distinct subunits. The proposed stratigraphic log is presented in Figure 8, which was extrapolated following the findings of both individual sections.

Table 1. *Detailed stratigraphic descriptions taken from the field expeditions*

Homsiyeh Section: Sample inventory (GPS: N 33°33' 006", E 035°32' 966" , Alt: 906m, Acc: 8m)				
Subunit	Bed No.	Sample No.	Lithology	
H-14	14.1	# 16.1	Alternating cross-bedded arenites and clays (mid-strata)	Cross-bedded ferruginous arenites
H-13	13.2	# 15.1		Clay
	13.1	# 14.1-2		1. Pink weakly laminated (fine-grained) sandstone and 2. Hard (poorly-sorted) reddish laminated sandstone
H-12	12.4	# 13.1-4		Cross-bedded arenites
	12.3			
	12.2			
	12.1			
H-11	11.1	# 12.1-2	Coarse-grained lag deposits comprising sandy strata	
H-1-10?	10.13	11.1	Laminated coal-rich clay showing lenticular bedding)	
	10.12b	10.1	Laminated clay rich in secondary iron deposits, overlying glauconitic marly horizons, may show some bioturbations.	
	10.12a		Clay	
	10.11	9.1	Limestone (possibly containing plant roots and high amounts of organic matter)	
	10.10.	8.1	Alternating sandy-clayey and carbonate lag deposits	Graywacke pebble conglomerate (showing some biomoulds and/ or fossils)
	10.9	# 7.1-2		Alternating laminations of sands and clays, overlain by a graywacke pebbly horizon with some calcite deposits
	10.8	# 6.1		Clay rich coal
	10.7	# 5.1	Cross-bedded channel and coarse grained sandstones	
	10.6b	# 4.1	Alternating beds of layered clay and cross-stratified sandstones	Pinch-out black coal-rich clay
	10.6a			Coal-rich clay (includes spotted white inclusions)
	10.5	# 3.1		Fine-grained cross-laminated sandstone
	10.4	# 2.1		Coal-rich clay
	10.3	#1.1-3	Alternating beds of laminated sandstones and clays	Fine-grained reddish sandstones that may show reverse grading, and
	10.2			Coal-rich clay
	10.1b			Grayish laminated sandstones which contain coal and amber (locally)
	10.1a			Clay

Figure 8. *Extrapolated stratigraphic log of the Homsiyeh sections illustrating the layers presented in Table 1*



Petrography

Table 2 presents the recalculated petrography estimations for all studied sections (including the Toumatt-Jezzine Aazibi section). Generally quartz readings in the order from 30 to 85% were recorded. Anomalous readings of quartz values less than 5% indicate carbonate or limestone strata.

Table 2. *Quantitative petrographic and sedimentological table showing the average composition of the studied strata of the Homsiyeh Section 2. For more detailed strata composition (especially for clays), refer to Table 3.. Calculated percentages were based on the visual estimation chart. Note that n/a indicates no apparent data upon petrographic assessment*

# Name	% Quartz	% Opaque/ bitumen	% Clay	% Calcite	% voids
# M 3	61	20	9	10	n/a
H 1.2	70	9	21	n/a	n/a
H 1.4	30	40	30	n/a	n/a
H 2.2a (#7)	79	16	4	3	n/a
H 2.2b (#8, 9)	80	15	3	2	n/a
H 2.2b (#10)	90	8	2	n/a	n/a
H 3.1	79	14	3	3	n/a
H 3.2	0-5	5-10	10-15	80	n/a
H 3.3b	0-5	15	0-5	80	0-5
H 4.2	5	0	20	70	n/a
Bed 1	63	21 (O.M.= 10%)	9	0	7
Bed 3	69	21 (O.M.= 2.5%)	3	0	7
Bed 5	58	25 (O.M. =9%)	7	0	10
Bed 7	64	21.17 (Fe = 8.5%)	2.5	0	13
Bed 11	1	15	5	79	5
Bed 14	50	34 (Fe =22%)	5	0	11
Bed 15	85	9 (O.M. = 3.5%)	2	0	4
Bed 16	85	9.5 (Fe = 6%)	1.17	0	4
Bed 17	73	11 (Fe = 4%)	1	0	15
Bed 18	79	9	4	0	6
Bed 19a	57	22 (O.M. = 10%)	15	0	6
Bed 19b	68	20 (Fe = 13%)	2	0	10
Bed 21	63	14 (O.M. = 3%)	3	0	20

The main strata of the Chouf Formation (mostly sandstones) were identified using both granulometric and petrographic tools. Hence, based on clay content 1) arenites (less than 5%), 2) argillaceous sandstones (5-15%), 3) graywacke (15-75%) and mudrocks (clay content over 75%) were properly classified following several sediment and/ or sandstone classification schemes (e.g. Shepard, 1954; Dott, 1964; Pettijohn et al., 1973; Folk, 1974, 1980; and Adams et al., 1994).

Arenites (Fig. 9), typically showing to be composed of two phases of quartz (identified in both in microscopic and XRD studies) labeled respectively as detrital quartz (DQ) and authigenic quartz (AQ) on Figure 9 show average intergranular porosities of 10-15%, as their clay content is typically less than 5%. However the argillaceous sandstones, and clayey-muddy sandstones as well as graywacke (with higher clay content), show lower amounts of porosity (generally assessed to be less than 5%). However, the clays (studied by XRD) indicate mostly porosity values of less than 2%.

Arenites contain 77% quartz, 10.5% opaque material, and about 2.3% clay and 9.8% voids. Arenites have on average an intergranular porosity of about 10% (Fig. 9). Therefore, they act as good reservoirs. Argillaceous sandstones contain 77% quartz, 16% opaque material, 2% clay, and 2% calcite as well as 3% voids (Fig. 10). They act as poor reservoirs. Clayey-muddy sandstones contain 59% quartz, 25% opaque material, 7% clay, 4.5% calcite, and 4.5% voids (Fig. 11). They act as poor reservoirs. Graywackes contain 55% quartz, 21% clay, 20% opaque material, and 4% voids (Fig. 12). Therefore, they act as poor reservoirs. The clays contain 75% clay particles, some 15% opaque material (and bitumen), 5% quartz and/ or other constituents, and, at most, 1% calcite/ carbonate materials. As porosity values are estimated to be close to 0%, reservoir properties are very low, and hence, these strata often act as seals anyway.

The limestones (Fig. 14) show evidence of different calcite phases exhibited by the different CL patterns and roots (see Fig. 5). Traces of micritization also occurred. All limestone strata are composed of calcite grains (80%), various traces of organic matter (15%); and clays and/ or other carbonates (2.5%), as well as some pores (2.5%) if found.

X-ray Diffraction

Table 2 shows the typical summary X-ray diffraction (XRD) table sho0wing the 2-theta values associated with d-spacings. As the XRD method relies on the Bragg equation (cf. Bragg, 1917), the relationship of the diffraction angle and distances are expressed as follows:

Braggs's Law:

$$n\lambda = 2d\sin\theta$$

Where:

n = an integer - 1, 2, 3..., etc

λ (lambda) = wavelength in angstroms

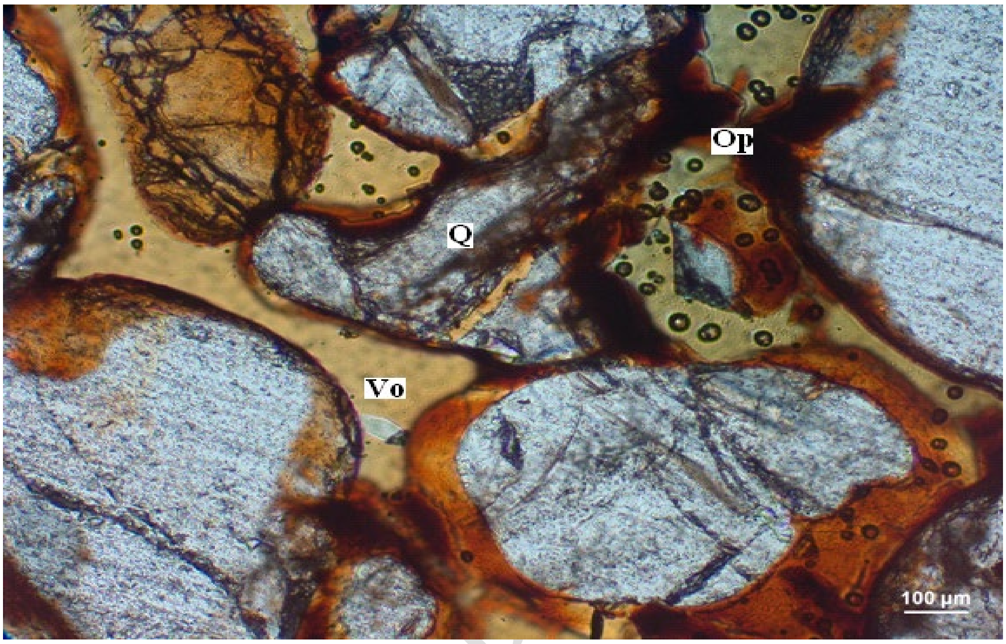
d (d-spacing) = interatomic spacing in angstroms

θ (theta) = the diffraction angle in degrees

Note that, for accuracy purposes, usually the double of the calculated theta angle is assumed for the XRD analysis (Moore and Reynolds, 1997).

Figure 9. *Transmitted light (A, PPL) and CL (B) photomicrographs of the same sandstone facies in the Homsiyeh Section 2 (Jezzine). Note the presence of quartz (Q), voids (Vo) and some opaque material (Op; including iron rich deposits and/ or organic matter) in the PPL photo (A), and of detrital quartz (DQ) and authigenic quartz (AQ) in the CL photo (B)*

A.



B.

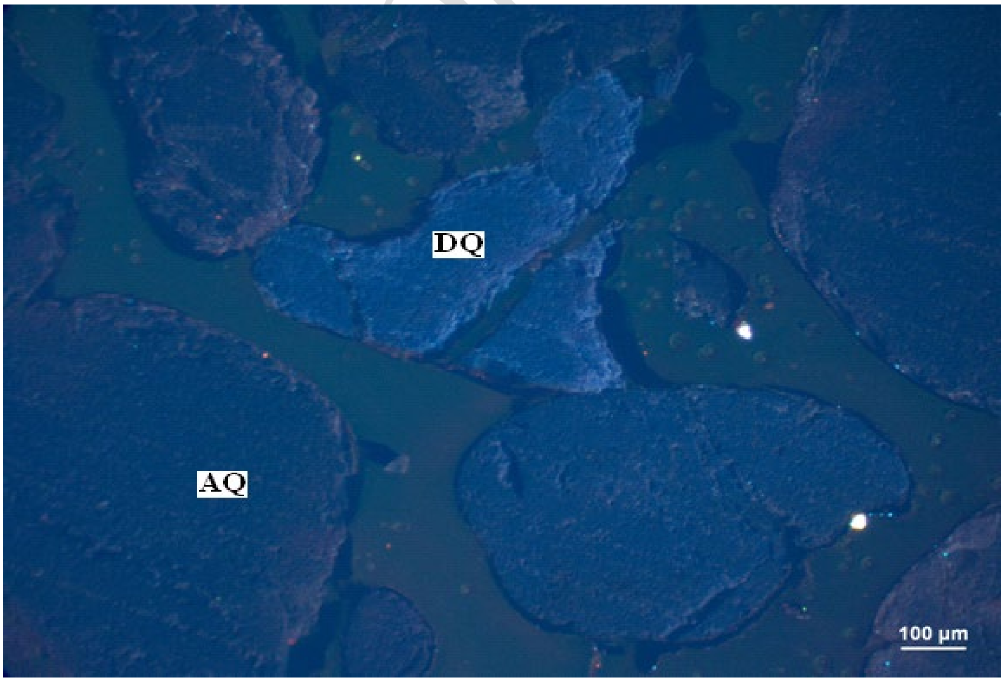


Figure 10. *Transmitted light photomicrograph (PPL) of a sandstone facies (# H 10.3, sample 1.3) in the Homsiyeh Section 2 (Jezzine). Note the presence of corroded quartz (Q), opaque materials (Op; including iron rich deposits and/ or organic matter), compaction (Cp) and voids and/ or cement (V/ C). the actual voids seem to be occluded by authigenic cements*

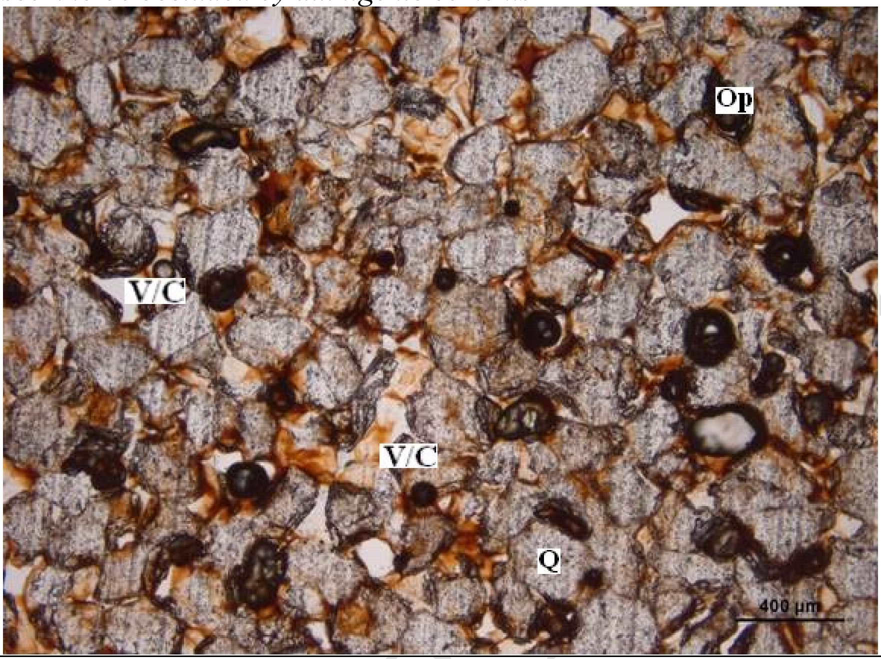


Figure 11. *Transmitted light (PPL) photomicrograph of a bitumen impregnated sandstone facies (# H 10.1, sample 1.1) from the Homsiyeh Section 2 (Jezzine). Note the presence of quartz (Q), opaque material (Op; including iron rich deposits and/ or organic matter), voids and/ or cement (V/C), and corrosion (Co), most likely caused by the maturating organic matter. Width of field of view is approximately 5mm*

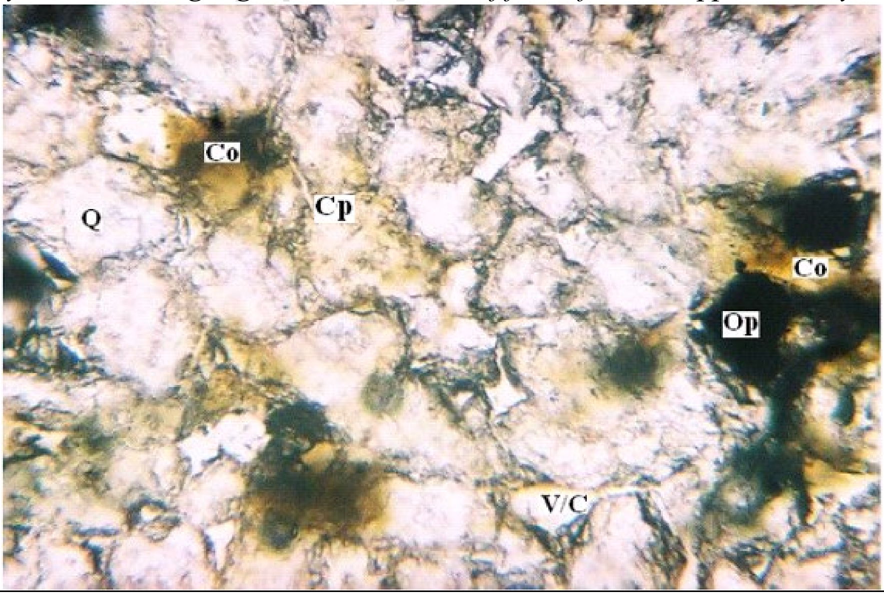


Figure 12. *Transmitted light (PPL) photomicrograph of a sandstone facies (# H 13.1a, sample 14.1) in the Homsiyeh Section 2 (Jezzine). Note the presence of quartz (Q), corrosion (Co), voids/ cement (V/C), and opaque materials (Op; including iron-rich deposits and organic matter)*

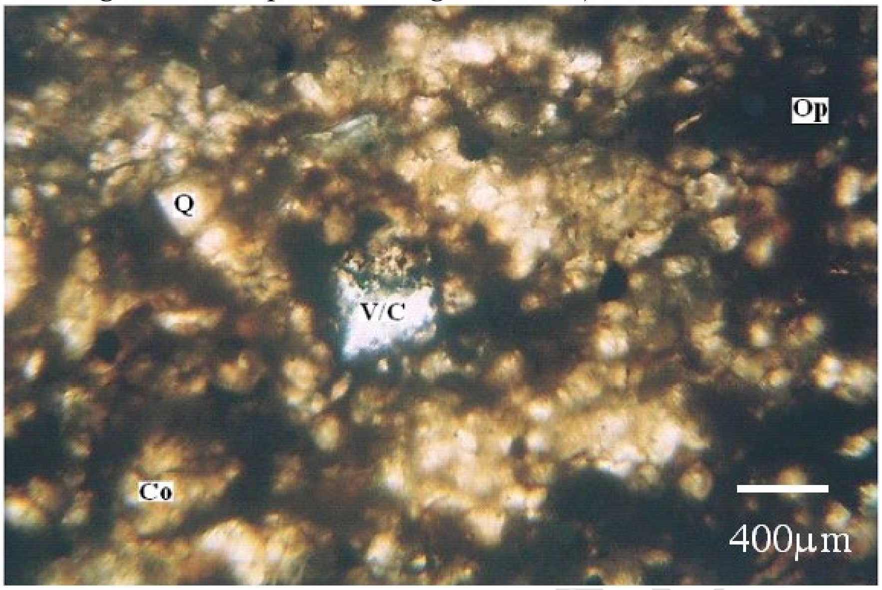


Figure 13. *Transmitted light (PPL) photomicrograph of a of clay facies (H 10.9; sample 7.2) in the Homsiyeh Section 2 (Jezzine). Note the presence of some traces of organic matter (OM), fossils (Fo), and probably calcite crystals (Ca) as well. Arrow indicates a probable fossil mould (Fm)*

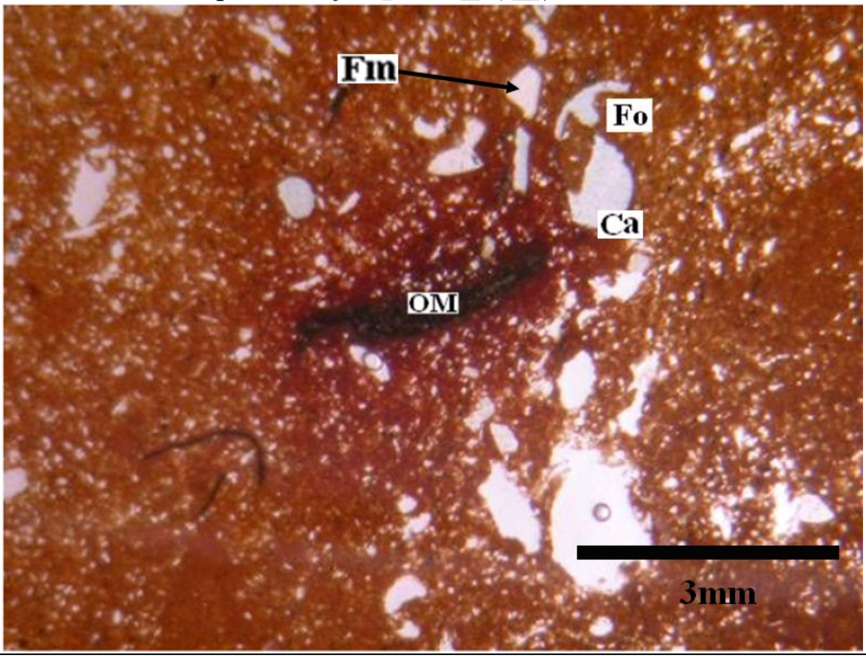
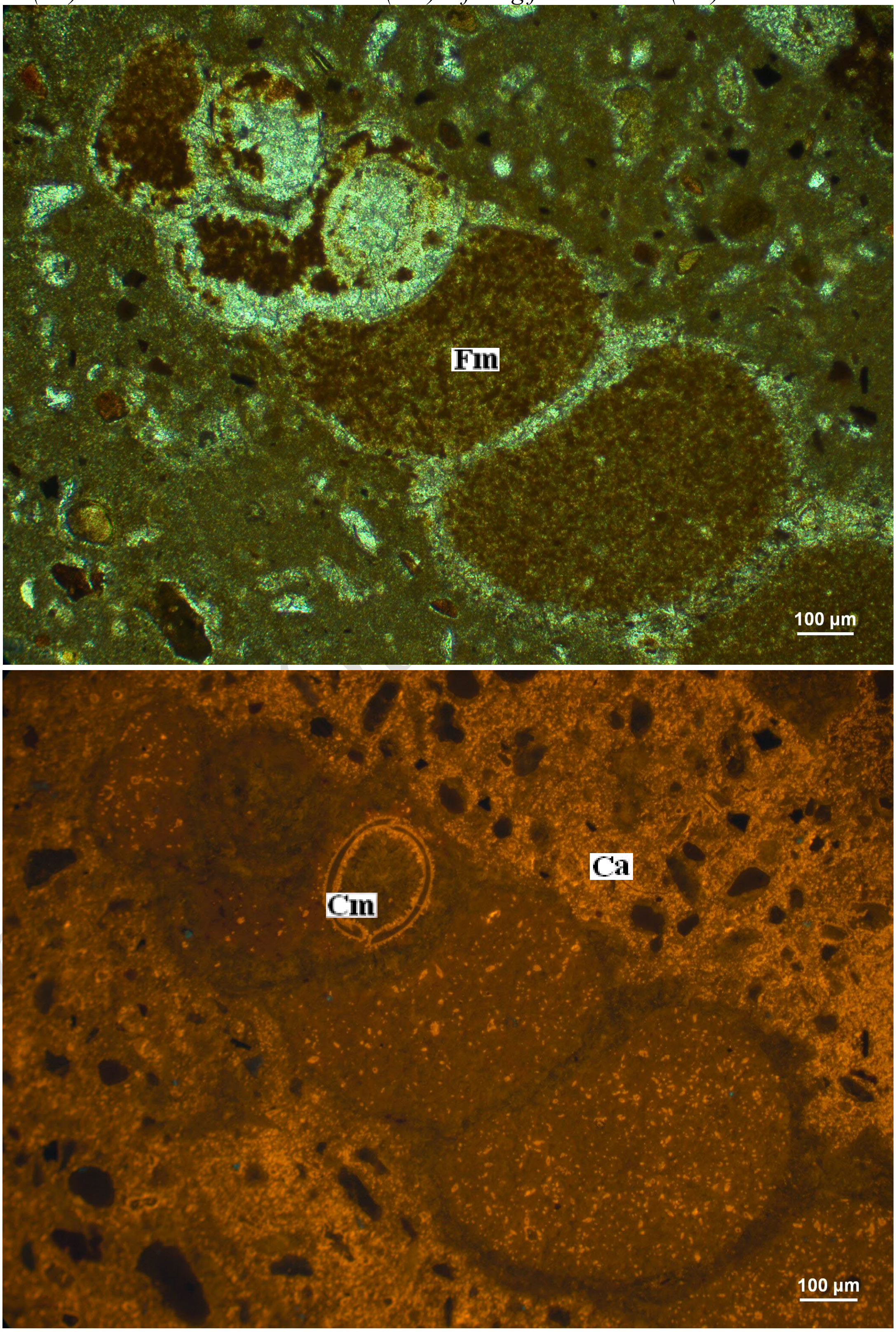


Figure 14. *Transmitted light (PPL; A) and CL (B) photomicrographs showing a limestone facies, Homsiyeh section 1 (Jezzine), displaying a limestone rich in calcite (Ca) with non luminescent cement (Cm) refilling fossil moulds (Fm)*



A.

B.

Table 3. *Summary X-Ray Diffraction Data table showing the 2-theta values with associated d-distances, of the representative facies of the Chouf Formation (e.g. Tixier, 1971-1972; Moore and Reynolds, 1997; Muhs et al., 2003; Muhs, 2004)*

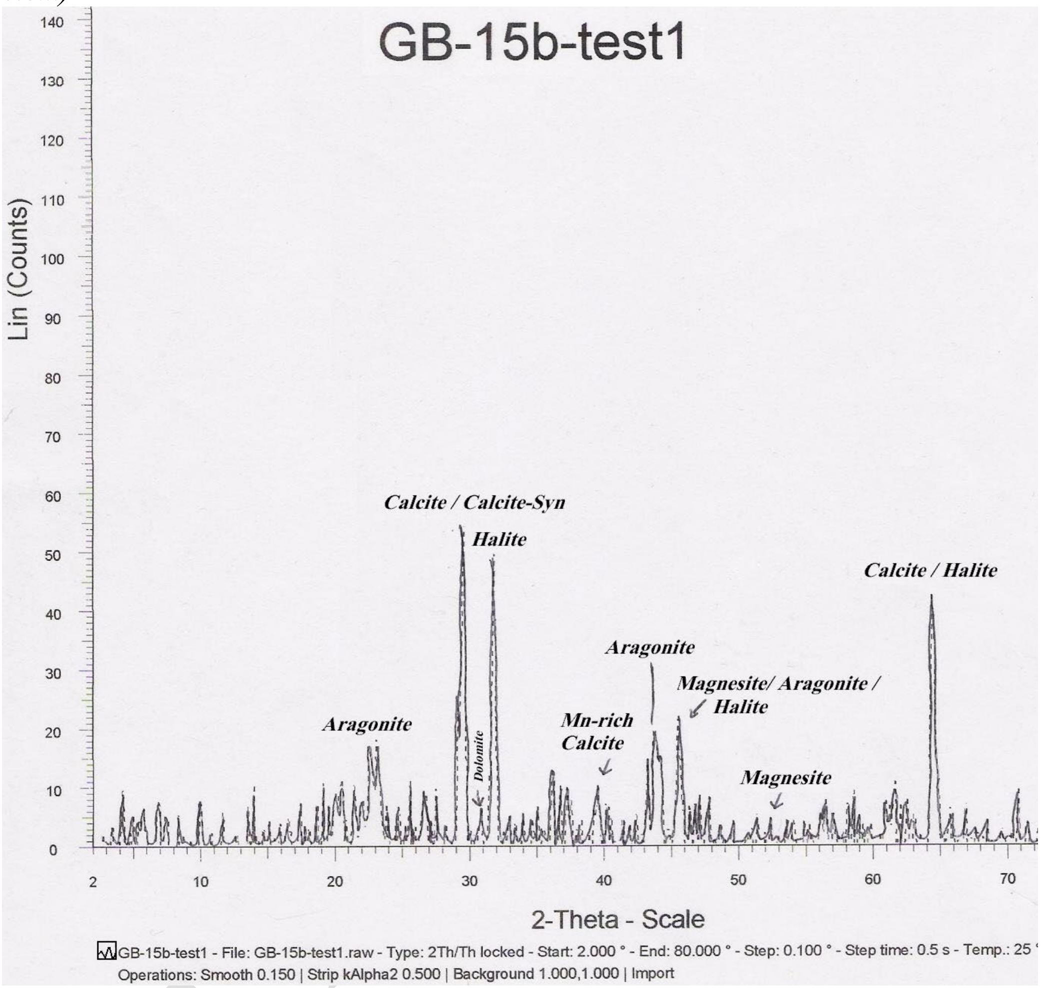
Mineral	2θ	d
quartz I	20.8	4.24
goethite	21.24	4.17
calcite I	23	3.86
kaolinite	23.15	3.84
quartz II/ illite	26.6	3.34
calcite II	29.43	3.04
halite	31.8	2.82
montmorillonite	38.3	2.34
calcite III	43.1	2.09
vaterite	43.84	2.06
quartz III	50	1.82
clay	64.5	1.44

Most tested strata indicate the presence of various phases of detrital components and authigenic components of the various bulk mineral composition of the Chouf Formation (see: Tables 2-4). As seen in Figure 7, most XRD tests carried out on sandstones reveal the presence of two or more quartz phases and varying amounts of clay (determoined also by cathodoluminescence). However, limestone plots (as shown in Figure 15) mostly reveal the presence of various phases of calcite, which were previously determined by cathodoluminescence microscopy.

Table 4. *General table representing the mineralogical data of the key facies from the Chouf Formation, along with their respective reservoir properties*

No.	Microfacies	Mineralogy	Reservoir Properties
I	Arenites	quartz, goethite and minor clays	very good
II	Muddy-quartzic sandstones	quartz, goethite, calcite, and clays	poor
III	Coarse muddy-quartzic sandstones	quartz, goethite, pyrite, and clays	poor
IV	graywacke	quartz, calcite, pyrite, glauconite, chlorite, feldspars, clays	poor
V	clay	clays, and other minerals (i.e. quartz, calcite, ...)	poor/ seal
VI	limestone	calcite, aragonite, clays	very poor

Figure 15. *Uncorrected X-ray diffractogram showing the mineralogical content of a sandstone facies (# H 3.3b, sample 15) in Homsiyeh Section 1 (Jezzine). Three (or more) calcite phases are identified, indicating different types (e.g. Mn-Calcite, etc...)*



Discussion

This data is organized into microfacies (with paragenesis), which is summed up by discussing the petroleum prospects. Table 4 presents some of the facies and associated depositional environments used as references for the identification of tentative sequence stratigraphy patterns during the Neocomian-Barremian.

Facies Analysis

<u>Facies analysis of Toumatt-Jezzine/Aazibi</u>

The tested sandstones, from the Toumatt-Jezzine/ Aazibi section, were found to be immature eolian sandstones (# M 3). This was to compare with the findings of the Homsiyeh sections. Figures 4 and 7 show the results obtained from the Granulometry and XRD tests that were carried out. These immature eolian sands were found to be improperly transported away from their weathered granitic sources (e.g. Muhs et al, 1997). They are most probably arkosic in composition, which appear to be both texturally and mineralogically immature (e.g. Muhs *et al.*, 1997a, b). Such sandstones exist, and, are in theory, located close to the source, or did not travel for far distances (Muhs *et al.*, 1997). According to Folk (1980), they may comprise mineralogically immature minerals (such as feldspars).

Some other strata from the Toumatt-Jezzine/ Aazibi were tested by XRD and reveal similar compositions to those of the Homsiyeh sections, indicating similarities in both sandstone bodies. Their X-ray diffractogram peak readings should not differ too much from the tested sandstones from the other sections (i.e. as those displaying quartz (20.8º 2θ), K-feldspar (27.4º 2θ), and plagioclase (27.8º 2θ)), even though they are not necessarily immature (e.g. Muhs, *et al.* 1997; Muhs, 2004).

Table 4. *Observed facies from the Chouf Formation, with their respective depositional environments.*

No.	Lithofacies	Microfacies	Depositional Environment	Reservoir potential
I	Quartz Arenite	Arenites	Eolian dune	Very good
II	Moderately sorted sands	Muddy-quartz-rich sandstones	Fluvial or dune	Poor
III	Poorly sorted sands and graywacke	Clayey-muddy quartz-rich sandstones	Aquatic regimes (Fluvial, overbank, alluvial and/ or turbidity currents)	Poor
IV	Clay	Clay	Very quiet areas associated with flooding (i.e. clay draping)	Poor/ Seal
V	Fossiliferous limestone	Wackestone	Shallow marine	Very poor

<u>Facies analysis of both sections at Homsiyeh</u>

The lower Facies are marine (i.e. aquatic strata): immature-submature sandstones, graywacke, shale and limestone beds (e.g. Dunham, 1962; Folk, 1962, 1968, 1980). The depositional environments were found to be mostly fluvial, or over-bank systems hence, Deltaic forming in low kinetic energy system, which do not by pass moderate rates (Folk, 1951; Boggs, 1995). Clays were found, and could indicate some form of burial diagenesis (see paragenesis). As these strata are dominantly from aquatic systems, they were deposited in relatively higher sea levels, although those sea levels depositing the Salima limestones were higher and point to shallow marine conditions (e.g. Noujaim-Clark & Boudagher-Fadel, 2001). Evidence for this lies in the presence of preserved organic matter, amber deposits and carbonates were recorded in fieldwork and labwork studies, and all seem to point to aquatic settings, of some continental influence.

Within some sandstone bodies, secondary iron deposits, slumping and clay draping were detected (Fig. 16). This could be a sign of flooding (Fig. 17), as further evidence pointing to it is the presence of herringbone cross-stratifications, and/ or tide and ebb currents, as well as glauconitic marly beds (e.g. Doummar, 2005).

The lower facies of the formation consist mainly of immature to submature sandstones, graywackes, shales, and limestones, indicative of fluvial to deltaic depositional environments formed under low-energy aquatic conditions (Dunham, 1962; Folk, 1962, 1968, 1980; Boggs, 1995). The presence of clays suggests burial diagenesis, while organic matter, amber, and carbonates indicate deposition during relatively high sea levels, particularly in shallow marine settings (Noujaim-Clark & Boudagher-Fadel, 2001). Field and lab evidence, including iron deposits, clay drapes, slumping, and herringbone cross-stratifications, further point to episodes of flooding and tidal influence (Doummar, 2005).

Figure 16. *A. Sandstones with secondary iron (Fe) deposits. Homsiyeh Section 1 (Jezzine). B. Photograph showing convolutions and disturbances (or slumping) in sandstones. Homsiyeh Section 1 (Jezzine). Width of view is approximately 1.5m. C. Clay draping in sandstones Photograph of a cross-bedded sandstone facies (located near the sandstone facies of Subunit H 2) in the Homsiyeh Section 1 (Jezzine) Note the presence of clay drapes (arrow for approximate location)*

A.

B.

C.

Figure 17. *Clay draping in Sandstone*

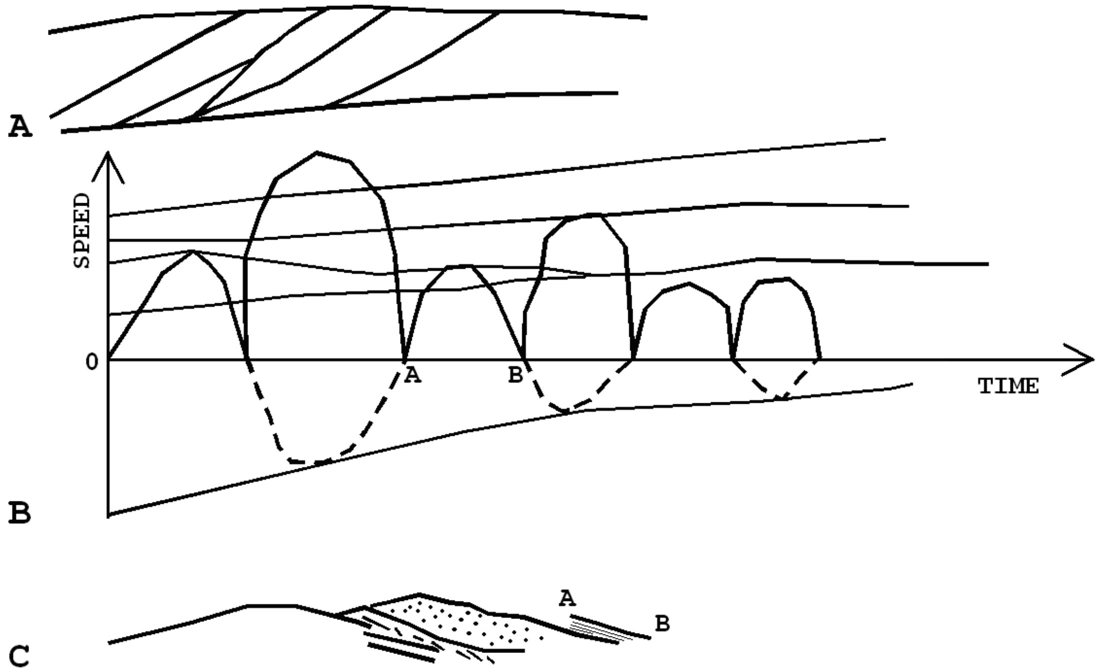


Figure 17 shows an illustrative sketch representing clay draping in channel sandstone facies, associated with tidal/ flooding events (Boggs, 1995). A. Sketch of typical cross-beds found in cross-stratified sandstone strata. B. Flooding/ tidal curve showing differing current flow speeds. At its lowest points (e.g. A & B), clay drapes are said to be formed (the clays cover the lee side of ripples). C. Sketch of ripple laminations (A, B) showing clay draping (see Fig. 16). Diagram based on Reading (2002).

The Mid-facies (continental) are composed of thick "eolian" sandstones, which are mostly submature-mature sandstones, were found to be typically devoid of clays (Folk, 1968, 1980). As they traveled large distances, their grains get rounded, therefore, sorting became higher (explaining why the arenites at in Homsiyeh are mostly mature), whereas the eolian sandstones of the Toumatt-Jezzine/Aazibi section were found to be mostly immature (according to sample coverage), meaning that transportation distances were low, accounting for a higher clay content and relatively poor sorting. The Depositional Environment are either Fluvial or eolian dunes which were laid down in mod-high Energy systems, as a result, they are generally devoid of clays (Folk, 1968; 1980).

Although arenites are the most common sandstone facies of the Jezzine area, and are found in purely continental deposits, there were other sandstone strata as well. The sea levels at mid Hauterivian time were found to be lowest (i.e. at some -90m), indicating a regression, explaining the continental dominated systems (Vail et al, 1977; Haq *et al,* 1987; Walley (1997); and Ferry *et al.,* 2007). Whereas, the other strata were found in mostly fluvio-deltaic systems, with fluvial and overbank systems, typically of moderate to high sea levels. Finally, both the lower and the mid strata contain evidence of the presence of coal beds, although originating from the aquatic beds.

Paragenesis and Hydrocarbon potential

Paragenesis

The sequence of diagenetic phases for the Neocomian-Barremian rock successions exposed in southern Lebanon (Jezzine locality) was deduced from the petrographic observations of 40 thin sections. The summary of these diagenetic phases and their sequential order are presented in Figures 7.2 and 7.3. All examined strata (sandstone, clay and limestone) were deposited and transformed during diagenesis. These diagenetic events, showing the results and interpretations of this project, are presented below. Figures 18 and 19 show the typical diagenetic phases recorded upon the petrographic analyses carried out on the Chouf Formation from early diagenesis (eogenesis) to late diagenesis (telogenesis).

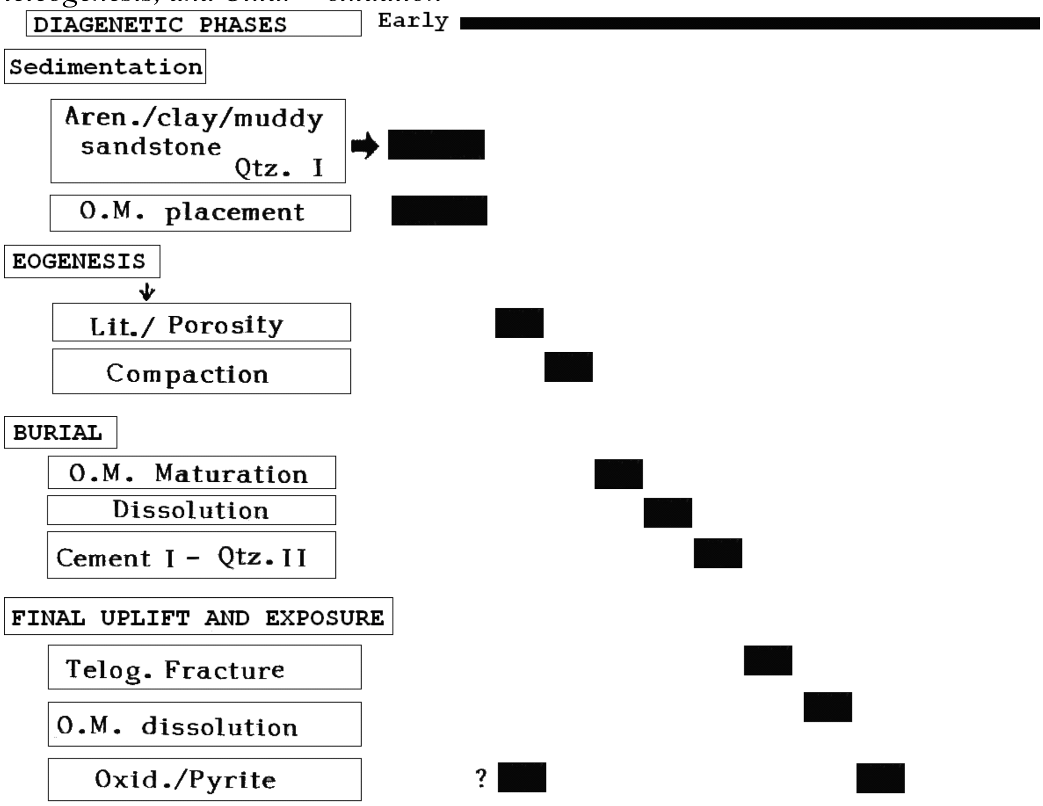
Burial History

The burial history of the Neocomian-Barremian rocks that are exposed in the Jezzine area (Fig. 20) is inferred based on the stratigraphic thicknesses of the various rock units exposed in the study area, on the known tectonic history, and the constructed paragenesis of the investigated sandstone and limestone microfacies (see Figs. 18 and 19). The investigated strata of Chouf Formation was probably buried at a maximum of 1800m depth prior to the mid-Eocene, when the Syrian Arc Deformation began (e.g. Walley, 1998; Brew *et al.*, 2001a, b; and Nader *et al.*, 2006). The burial curve summarizes the paragenesis and is shown in Figure 7.4. The curve presents all the diagenetic phases and relates them to the burial history of the Chouf Formation.

Pyrolysis

As the Chouf Formation was buried at about 1800m (Eocene), the temperature of organic matter maturation is estimated at about 65-70ºC (assuming a geothermal gradient of 25ºC/km and a surface temperature was 25ºC at the time of deposition). Thus, the organic matter may have been mildly cooked releasing corrosive fluids. Figure 20 shows the pyrolysis results obtained from a coal sample from the clay beds of the lower part of the Chouf Formation, where a value of 67.5% total organic carbon (TOC) was found.

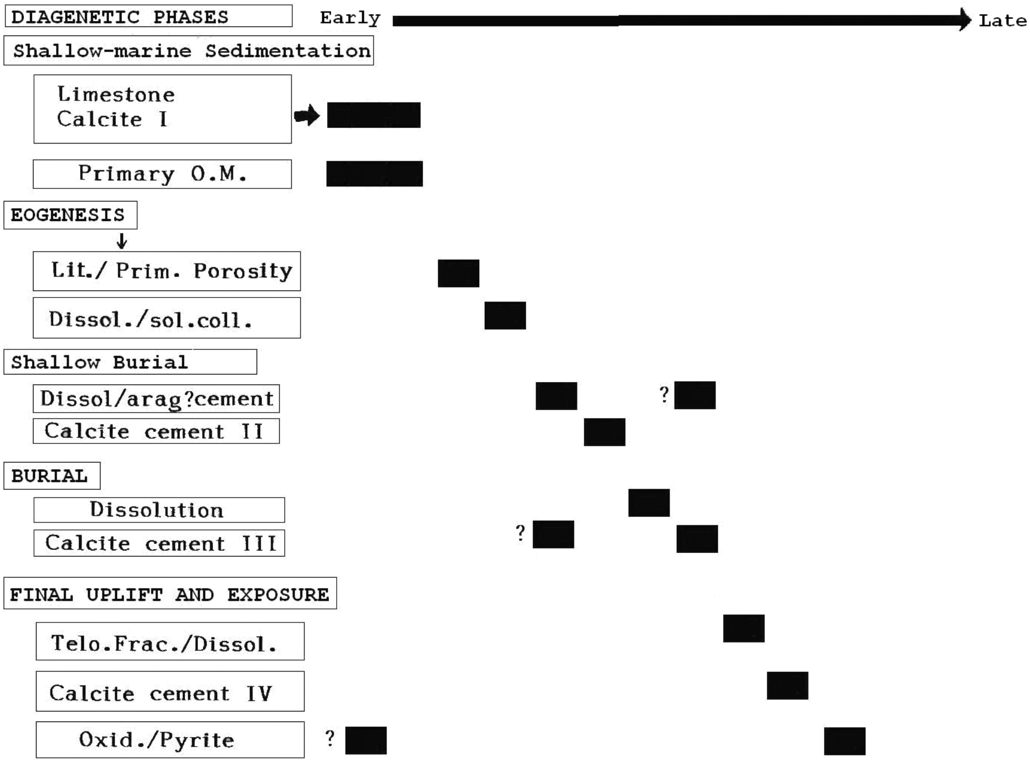
Figure 18. *Sequence of diagenetic phases for the sandstone facies exposed in the Toumatt-Jezzine/ Aazibi and Homsiyeh sections (southern Lebanon). Aren. = Arenite, O.M. = organic matter Qtz. = quartz, Lit. = Lithification, Telog. = teleogenesis, and Oxid. = oxidation*



Inferred Reservoir Potential

As porosity and permeability are important factors in reservoir rocks, and are generally high for sandstones, bulk rock porosity is usually decreased from 40 to 10% through cementation (e.g. Hobson and Tiratsoo, 1985; Ramm and Bjorlykke, 1994). Deep burial increases overall pressure, and as a result, the bulk rock porosity of sandstones may drop from 35% to 25% at depths of about 5km (e.g. Ramm and Bjorlykke, 1994). In this study, it was found that the arenites act as good reservoirs (10% intergranular porosity), whereas the argillaceous sandstones, graywackes and wackestones act as less good reservoirs, as their average intergranular porosity is less than 5%, caused by their larger amounts of clay (which is, in most cases, over 5%). However, as clays have very low porosity, they act as very poor reservoirs, but are mostly regarded as seals. Several hydrologic and hydrogeologic studies demonstrate that the Chouf Sandstone acts in general as an aquitard due to the presence of clays, which hampers infiltration (e.g. Searle, 1972; Shuayb, 1974; Tabet, 1978; Abbud and Aker, 1986; Hamzeh, 2000). The same also should apply to reservoir potential, once the Chouf Formation is considered as a whole, even though the arenite strata may act as good reservoirs.

Figure 19. *Sequence of diagenetic phases for the sandstone facies exposed in the Toumatt-Jezzine/ Aazibi and Homsiyeh sections (southern Lebanon). O.M. = organic matter, Prim. = primary, Dissol. = dissolution, sol. coll. = solution collapse, arag. = aragonite, Telo. = telogenic, Frac. = fracture, and Oxid. = oxidation*



Concluding Remarks

Conclusions

This project includes the results of detailed field work, as well as petrographic and mineralogical studies conducted on several representative key Neocomian-Barremian rock facies of the Chouf Formation in the Jezzine region (southern Lebanon). Based on field observations of sandstone strata, and regional correlation, as well as petrographic and XRD characterization of the investigated rocks, the following conclusions are drawn.

Six microfacies are identified in the current study, within both investigated sections, at Homsiyeh. They are listed and described as follows: i) arenites, ii) muddy quartz-rich sandstones, iii) clayey-muddy quartz-rich sandstones, iv) graywacke, v) clay, and vi) limestones.

Arenites, the most abundant microfacies of the Chouf Formation, mostly representing the middle part of the formation, are composed of submature to mature sandstones almost devoid of clays showing eolian characteristics and are quartz-rich (content is over 95%, according to the Folk (1980) sandstone classification chart). They are typically well-sorted and develop in areas of moderate to high kinetic energy. Since they are well-sorted and the average intergranular porosity is around 10%, they may act as very good reservoir rocks. XRD studies show two or more phases of quartz, clays and goethite, and, in some cases, probable traces of calcite. The two identified phases of quartz (detrital and authigenic) were identified under CL microscopy (Fig. 5.26; Chapter V). In some cases, feldspar was also detected by its light blue CL pattern (see Fig. 5.25B; Chapter V), which is confirmed through XRD analysis.

Figure 20. *Burial curve with recorded diagenetic history of the Chouf Formation. Note that the recorded burial is estimated at 1800m, thickness is 300m, and the resulting curve is uncorrected for compaction (Creta. = Cretaceous, Pli = Pliocene, R. = Recent, and O.M. = organic matter). Figure constructed based on data and forms presented in Doummar, (2005), and Nader et al. (2006)*

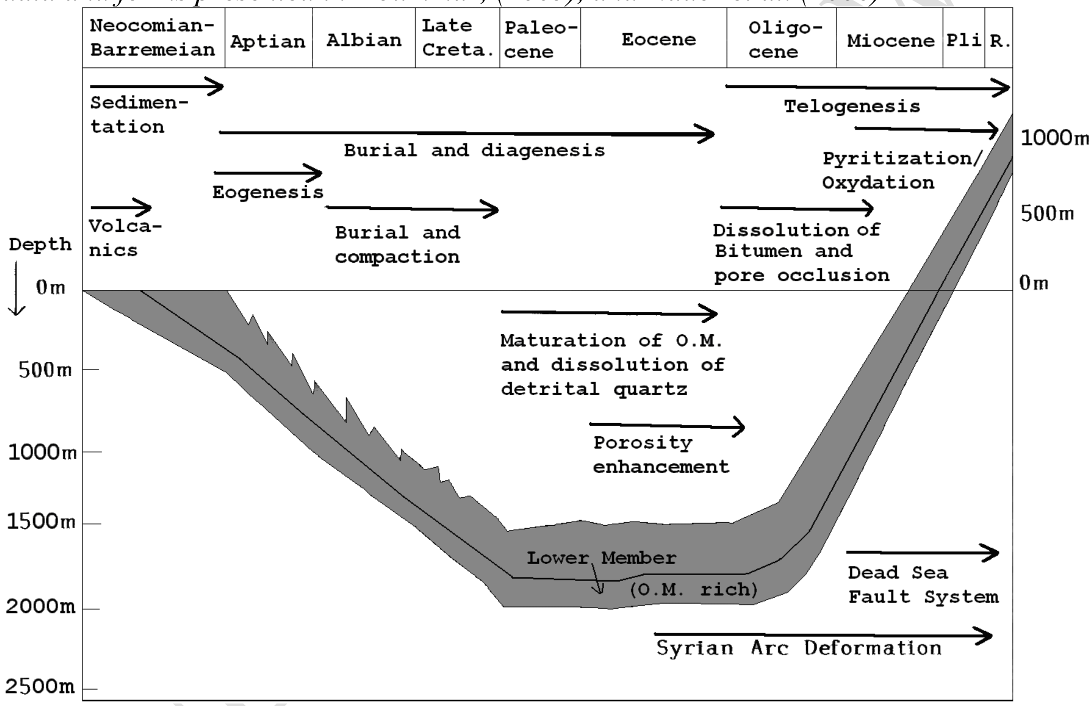
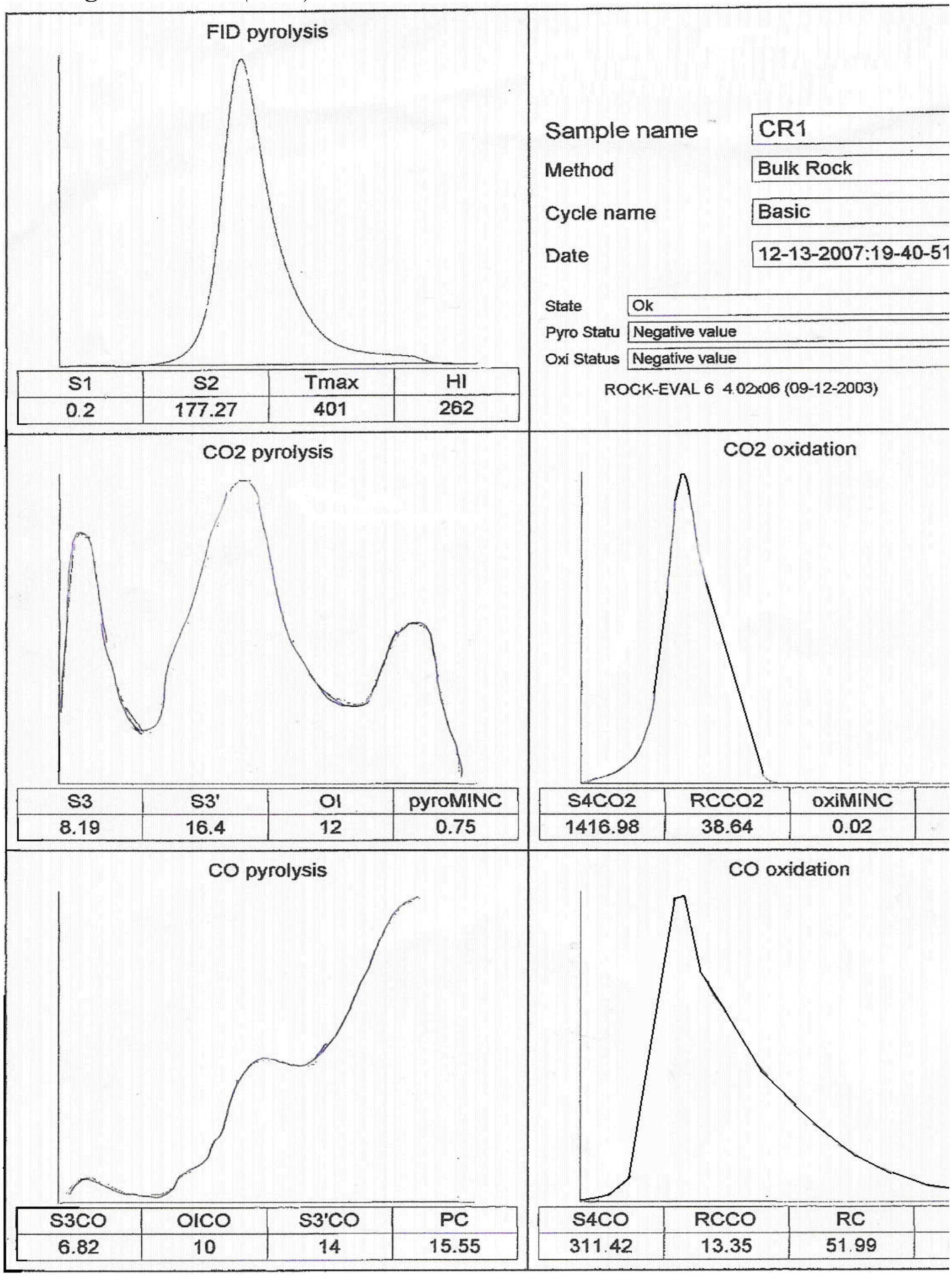


Figure 21. *Extrapolated pyrolisis results of an organic matter sample from the Lower part of the Chouf Formation. The pyrolisis was conducted at the Sedimentology Laboratory of the Institut Français du Pétrole (IFP). Note that the total organic carbon (TOC) was estimated at 67.54%*



Most of the submature sandstones were classified as muddy quartz-rich sandstones, as they were moderately sorted and contained some clay (less than 5%). They are dominantly fluvial (and likely marine, as well) and of moderate energy environments. Since they are moderately sorted and the average intergranular porosity is about 10%, they may also act as good reservoir rocks. XRD tests helped in identifying the presence of two or more quartz phases, several clays (including nontronite (lacking smectite)), and calcite.

Clayey-muddy quartz-rich sandstones include all immature sandstones that have clay contents over 5% and are poorly sorted. They are found in dominantly fluvial or overbank channel environments, of low-energy. Since they are poorly sorted and the average intergranular porosity is about 5% or less, they may act as poor reservoir rocks. XRD tests show the presence of different phases of quartz, including calcite among others, pyrite and clays.

Graywackes include all strata which are extremely poorly sorted and include clay contents over 15% (feldspars and micas and other components account for about 25%). They are typically fine grained strata found in turbidity deposits of low kinetic energy. Since they are poorly sorted and the average intergranular porosity is about 5% or less, they may act as poor reservoir rocks. XRD tests indicate that these strata show different phases of quartz, including other constituents as calcite, pyrite, glauconite, chlorite, feldspars, and clays.

Clays (generally containing lignite) were identified using X-ray diffraction. Thus, various amounts of bentonite, illite, kaolinite montmorillonite, nontronite and vermiculite were found. Most beds show the presence of kaolinite, illite and montmorillonite (e.g. Tixier, 1971-1972). However, chlorite, goethite, vermiculite often recur in some beds. In a few instances, illite/ montmorillonite interstratified layers were found (these interstratified layers have a diagenetic signature, just like the illite/ smectite or montmorillonite/ illite ratios). Since they are characterized by very low average intergranular porosity, they may act cap rocks or seals. The clays also led to a dramatic decrease in the aquiferous properties of the Chouf Formation (e.g. Shuayb, 1974).

The limestones (defined as fossiliferous micritic muddy-wackestones, based on the carbonate classification schemes of Dunham (1962), and Folk (1962)) dominantly comprise calcite (four phases – XRD, CL microscopy) and aragonite, including other minor amounts of other carbonates, such as dolomite (based on XRD). The limestones, which were found to be se shallow marine carbonates, show plant activity, and appear to be associated with various glauconitic marly beds that were found nearby. Since they are poorly sorted and the average intergranular porosity is about 2.5% or less, they may act as very poor reservoir rocks.

In earlier studies dealing with hydrocarbon potential, the organic matter found in terrigenous clastic rocks was thought to yield bitumens and oilshales (e.g. May, 1991). The results of this study point out that the organic matter of the Chouf Formation was transformed to lignite, as the burial/thermal history was recorded at 65ºC towards the mid-Eocene, causing the improperly maturing organic matter to produce coal rather than oil (due to high TOC and low HI values). Due to the telogenic fracturing, as a result of the Syrian Arc Deformation, uplifting, fracturing and erosion occurred.

This research demonstrated that the studied hydrocarbon, in the lower aquatic facies of the Chouf Formation (southern Lebanon), is immature. During mild cooking at low temperature aggressive fluids helped in increasing the general porosity through dissolution and yet still led to quartz cementation. Finally, the eolian arenites (of the middle part of the Chouf Formation) could act as reservoirs due to their relatively high intergranular porosity (of about 10%) caused by good sorting and roundness. These arenites contain low amounts of cements, if any.

Synthesis and future outlooks

The geological and hydrostratigraphic evolution of Northern Lebanon and adjacent Syrian basins—documented extensively by Abbud & Aker (1986), Walley (1983, 1997, 2001), Brew et al. (2001a, b), and Doummar (2005)—reveals a complex interaction between fluvio-deltaic sedimentation, episodic tectonism, and fluctuating sea levels (Haq et al., 1987; Vail et al., 1977). These processes generated alternating facies of sandstones, shales, and limestones (Folk, 1962, 1968; Dunham, 1962; Boggs, 1995), whose diagenetic evolution and mineralogical maturity (Muhs, 2004; Ramm & Bjørlykke, 1994) shaped the hydrogeological and geomorphological character of the coastal aquifer systems (Khair, 1988; Hamzeh, 2000). The lithostratigraphic reconstructions by Tixier (1972), Pettijohn et al. (1973), and Walley (1998) have further clarified the sedimentological framework linking Lebanon's Cretaceous basins with the broader Levantine margin of the Neo-Tethys (Stampfli et al., 2001). Within this intricate geodynamic context, heritage valorization strategies must account for both geological sustainability and socio-economic adaptation. As established by May (1991), Nader et al. (2006), and Noujaim-Clark & Boudagher-Fadel (2001), the natural foundations of these regions underpin not only resource availability but also cultural identity.

Recent discussions in consumer behavior studies (Ogunmuyiwa, 2022; Slazus & Bick, 2022) have underscored that heritage-driven tourism demand increasingly depends on ecological awareness, authenticity, and digital accessibility—variables that align with resource valorization frameworks, and applied to both cultural and natural resource valorization (Al Sawi, 2018). Integrating geological knowledge with advanced valorization strategies, is part of an upcoming study incentive that supports a holistic development model where natural and cultural heritage, environmental resilience, and tourism economies reinforce one another. Ultimately, valorizing Lebanon's coastal landscapes and also in areas in the Northern or southern Levant requires more than preservation; it entails transforming scientific insights into sustainable economic instruments (ref). By linking the sedimentary and tectonic evolution of the region with emerging AI-based mapping and consumer behavioral analytics, future research should promote adaptive management that harmonizes geological heritage, tourism enhancement, and socio-economic renewal—bridging the past and future of a resilient Mediterranean landscape (Ref).

Ultimately, valorizing Lebanon's coastal landscapes requires more than preservation; it entails transforming decades of geological, geochemical, and tectonic scholarship into instruments of sustainable development. Building upon foundational sedimentological and stratigraphic analyses (e.g., Folk, 1962; Walley, 1983; Boggs, 1995; Doummar, 2005; Nader et al., 2006), recent interdisciplinary research now situates the region's Cretaceous and Mesozoic sequences within broader Levantine and Tethyan frameworks (Brew et al., 2001; Stampfli et al., 2001; Ferry et al., 2007; Bellos, 2008), clarifying their paleoenvironmental and structural evolution. The integration of mineralogical, hydrogeological, and diagenetic studies (e.g., Khawlie & Touma, 1993; Hamzeh, 2000) underscores the diversity and economic potential of these aquiferous and reservoir-bearing formations, while tectonic syntheses (Chaimov et al., 1992; Walley, 1998, 2001) illuminate the dynamic setting that shaped their preservation. When coupled with emerging models of consumer behavior and environmental valuation (ATINER, 2022a; ATINER, 2022b), these scientific insights offer pathways to align heritage valorization with responsible tourism, participatory economics, and community stewardship. As proposed in Bellos & Noaman, (2025a, b), resource valorization must be what people and communities focus on in the near future.

Finally, AI-driven predictive mapping and behavioral analytics to translate geological and cultural knowledge into adaptive management tools. In this sense, the future of Lebanon's coastal landscapes lies not only in conserving their sedimentary memory but in transforming it into a living framework for socio-economic renewal, bridging scientific heritage and sustainable prosperity across the Mediterranean. (ref)

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References

Abbud and Aker, 1986. The study of the aquiferous formations of Lebanon through the chemistry of their Typical springs. Lebanese Science Bulletin, Vol. 2(2).

Adams A.E., MacKenzie, W.S., and Guilford, C., 1994. *Atlas of the Sedimentary rocks under the microscope*. John Wiley and Sons.

Al-Sawi, M. (2018). The Effective Valorization of Resources for the Economic Development of Tyre. *MBA Project presented at the Lebanese International University*, Spring 2018.

Bellos, G.S.G., 2008. “Sedimentology and Diagenesis of Some Neocomian Barremian Rocks (Chouf Formation), Southern Lebanon”. *Master’s Thesis presented at he American university of Beirut,* June, 2008, Lebanon.

Bellos, G.S.G., 2021. “Sedimentology and Diagenesis of Some Neocomian Barremian Rocks (Chouf Formation), Southern Lebanon”. Retrieved from: https://gebell900. blogspot.com/2021/03/sedimentology-and-diagenesis-of-some.html.

Bellos, G.S.G., & Noaman, S.-B., (2025a). “Discussing the impact of the effective valorization of the natural, cultural and tourism resources for the economic development of Beirut”. *International Journal of Engineering Research in Computer Science and Engineering (IJERCSE)*, 12(3), 1 –12.

Bellos, G.S.G., & Noaman, S.-B., (2025b). “Discussing the Influence of the Effective Valorization of Natural, Cultural, and Tourism Resources on the Economic Development of Tyre: Interpreting Secondary Data”. *International Journal of Engineering Research in Computer Science and Engineering (IJERCSE)*, 12(3).

Beydoun, Z.R., 1997. Earthquakes in Lebanon: An Overview, *Lebanese Science Bulletin* Vol. 10 (1); p.109.

Beydoun, Z.R., 1995. Productive Middle-East chiastic oil and gas reservoirs: their depositional settings and origins of their hydrocarbons. *Spec. Pubs int. Ass. Sediment.* Vol. 23, pp. 331-354.

Blatt, H. 1992. *Sedimentary Petrology*. W.H. Freeman, New York. Boggs, S., 1995. *Principles of Sedimentology and Stratigraphy*. 2nd edition, Prentice Hall, 774 p.

Bragg W.L., 1917. "The Diffraction of Short Electromagnetic Waves by a Crystal", *Proceedings of the Cambridge Philosophical Society*, 17, p43–57.

Brew, G., 2001. Tectonic evolution of Syria interpreted from integrated geophysical and Geological Analysis. Ph.D. Thesis, University of Cornell.

Brew G., Lupa, J., Barazangi, M., Sawaf, T., AL-Imam A., and Zaza T., 2001a. Structure and tectonic development of the Ghab basin and the Dead Sea fault system, Syria. *Journal of the Geological Society, London*.

Brew, G., Barazangi, M., Al-Maleh, M.K., and Sawaf, T., 2001b. Tectonic and Geologic evolution of Syria. *GeoArabia*, Vol. 6, (4), pp 573-615.

Chaimov, T., Barazangi, M., Al-Saad, D., Sawaf, T., and Gebran, A., 1992. Mesozoic and Cenozoic deformation inferred from seismic stratigraphy in the southwestern intracontinental Palmyride fold-thrust belt, Syria. *Geological Society of America Bulletin*, 104, N6, 704-715.

Cohen, Z., 1976. Early Cretaceous buried canyon: Influence on accumulation of hydrocarbons in Helez Oil Field, Israel. *American Association of Petroleum Geologists Bulletin*, Vol. 60, (1): pp. 108-114.

Dott, R.L., Jr., 1964. Wacke, greywacke and matrix - what approach to immature sandstone classification? *J. Sediment. Petrol*, v. 24, pp. 625-632.

Doummar, J.J., 2005. Sedimentology and Diagenesis of the Albian Rock Sequence (Upper Hammana-Lower Sannine Formations), Northern Lebanon. Unpublished M.S. Thesis American University of Beirut. 201p.

Dunham, R. J., 1962. Classification of Carbonate rocks according to their depositional texture, in W. E. Ham, ed., Classification of Carbonate Rocks: Tulsa. OK, *AAPG Memoir 1*, p. 108-121.

Eyal, Y., 1996. stress field fluctuation along the Dead Sea Rift, since the Miocene, *Tectonics*, v. 15, pp. 157-170.

Ferry, S., Merran, Y., Grosheny, D. and Mroueh, M., 2007. The Cretaceous of Lebanon in the Middle East (Levant) context. In: Bulot, L.G., Ferry, S., and Grosheny, D. (Eds.), Relations entre les marges septentrionale et méridionale de la Téthys au Carnets de Géologie, Brest, Memoir 2007/02, Abstract 08.

Folk, R.L., 1951. Stages of textural maturity in sedimentary rocks. *Journal of Sedimentary Petrology*, Vol. 21 (3), pp. 127-130.

Folk, R.L., 1955. Student operator error in determination of roundness, sphericity and grain size. *Journal of Sedimentary Petrology*. Vol. 25 (4), pp. 297-301.

Folk, R.L., 1962. Practical petrographical classification of limestones. *AAPG Memoir,* 1.

Folk, R.L., 1966. "A review of grain-size parameters"; *Sedimentology*, Vol. 6 (2).

Folk, R.L., 1968. *Petrology of sedimentary rocks*. Austin TX, Hemphill Publishing Co.

Folk, R.L. 1974. *Petrology of Sedimentary Rocks*. Hemphill Publishing Company.

Folk, R.L., 1980. *Petrography of Sedimentary Rocks*. Hemphill Publishing Company.

Folk, R.L., and Ward, W.L, 1957. Brazos river bar: A study in the significance of grain size parameters*: Jour. Sed. Petr*., Vol. 27, No. 1, pp. 3-26.

Hamzeh, M., 2000. Groundwater conditions in South Lebanon between the Awali and Litani rivers. M.S. Thesis, American University of Beirut, Beirut, Lebanon. 107p. Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science* Vol. 235, 1156–1166.

Haq, B.D., Hardenbol, J. and Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In C.K. Wilgus, B.S. Hastings, C.A. Ross *et al.* (Eds.), Sea-level changes: an integrated approach, *Special Publication - Society of Economic Paleontologists and Mineralogists*. 42, 72-108.

Hobson, G.D. and Tiratsoo, E.N., 1985. *Introduction to Petroleum Geology*. 2nd Edition, Revised. Gulf Publishing Co.

Khair, K.S., 1988. A Different Approach to the Interpretation of Geophysical Data Linking Surface and Subsurface Studies in Hydrogeology. Lebanese Science Bulletin Vol. 4 (1); p.79.

Khawlie M.R., and Touma, G., 1993. Determining the Behaviour of the Highly Variable Basal Cretaceous Sandstone (Nubian Facies) in Brummana, Lebanon. Lebanese Science Bulletin Vol. 6 (1); p.33.

May, P.R., 1991. The Eastern Mediterranean Basin: Evolution and Oil Habitat. *AAPG Bulletin*, Vol. 75, No. 7; pp 1215-1232.

Moore, D.M., and Reynolds, R.C., 1997. *X-ray diffraction and the identification and analysis of clay minerals*. Oxford University Press.

Muhs, D.R., 2004. Mineralogical maturity in dunefields of North America, Africa and Australia. *Geomorphology*, Vol. 59, pp. 247–269.

Muhs, D.R., Stafford, T.W., Jr., Swinehart, J.B., Cowherd, S.D., Mahan, S.A., Bush, C.A., Madole, R.F., and Maat, P.B., 1997a. Late Holocene eolian activity in the mineralogically mature Nebraska Sand Hills. *Quaternary Research* Vol. 48.

Muhs, D.R., Stafford, T.W., Jr., Been, J., Mahan, S., Burdett, J., Skipp, G., and Rowland, Z.M., 1997b. Late Holocene eolian sand deposition in the Minot dune field, North Dakota. *Canadian Journal of Earth Sciences* Vol. 34, 1442–1459.

Nader F.H., Abdel-Rahman, A.F.M. and Haidar, A. T., 2006. Petrographic and chemical traits of Cenomanian platform carbonates (central Lebanon): implications for depositional environments. *Cretaceous Research*, Vol. 27; pp. 689-706.

Noujaim-Clark, G. and Boudagher-Fadel, M.K., 2001. The larger benthic foraminifera and stratigraphy of the Upper Jurassic-Lower Cretaceous of Central Lebanon. *Revue de Micropaléontologie*, Vol. 44 (3), pp. 215-232.

Ogunmuyiwa, M-S. (2022).“The Influence of Publicity and Sales Promotion on Marketing Performance in Nigeria”, *Athens Journal of Business & Economics.* 8(1), 65–78,

Pettijohn, F.J., Potter, P.E., & Siever, R., 1973. *Sand and Sandstone*. Springer-Verlag.

Ponikarov, V.P. (Ed.), 1966. The Geology of Syria: Explanatory Notes on the Geological Map of Syria, Scale 1:200,000. Ministry of Industry, Damascus, Syria.

Ponikarov, V.P. (Ed.), 1967. The geology of Syria: Explanatory notes on the geological map of Syria, scale 1:500,000. Part I, Stratigraphy, Igneous Rocks and Tectonics, 229 pp., Syrian Arab Republic, Ministry of Industry, Damascus, Syria.
Ramm, M. Bjorlykke, K., 1994. Porosity/depth trends in reservoir sandstones--assessing the quantitative effects of varying pore-pressure, temperature history and mineralogy, Norwegian Shelf data. *Clay Minerals* (1994) 29, 475-490.
Searle, T.R., 1972. *The geotechnical properties of Cretaceous clay shales in Lebanon*. Ph.D. Thesis.
Shepard, F.P., 1954. Nomenclature based on sand-silt-clay ratios. *Jour.Sed. Petrol.* 42.
Shuayb, S. 1974. Hydrology structures of the Aintoura-Tarshish and Qurnayel region, northern Metn, Mount Lebanon. Unpublished M.S. Thesis, American University of Beirut, Beirut, Lebanon. 84p.
Slazus B.-J., & Bick, G. (2022) "Factors that Influence FinTech Adoption in South Africa: A Study of Consumer Behaviour towards Branchless Mobile Banking", *Athens Journal of Business & Economics.* 8(1), 43–64.
Stampfli, G. M., Borel, G. D., Cavazza, Mosar, W., J., and Ziegler, P. A. Palaeotectonic and palaeogeographic evolution of the western Tethys and PeriTethyan domain (IGCP Project 369). *Episodes*, 24(4).
Tabet, C., 1978. Geology and hydrogeology of the Baskinta-Sannine region, Central Lebanon. Unpublished M.S. Thesis, American University of Beirut, Lebanon.
Tixier, B., 1971-1972. Le Grès de Base" Crétacé du Liban: Étude Stratigraphique et Granulométrique. *Notes et Mémoires sur Le Moyen Orient*, Tome 12. Muséum d'Histoire Naturelle, Paris Ve, pp 207-213.
Touma, G., 1985. The geology, physical, and mechanical properties of the Lower Cretaceous Sandstone. Brummana area, Lebanon. M.S. Thesis, American University of Beirut, Beirut, Lebanon. 215p.
Ukla, S.M., 1970. Subsurface and well correlation in North and Central Lebanon. Unpublished M.S. Thesis, American University of Beirut, Beirut, Lebanon..
Vail, P.R., Mitchum Jr., R.M., Thompson, S., 1977. Seismic stratigraphy and global changes of sea level. Part 3: relative changes of sea level from coastal onlap. In: Payton, C.E. (Ed.), Seismic Stratigraphy—Applications to Hydrocarbon Exploration, vol. 26. *American Association of Petroleum Geologists Memoir*.
Walley, C. D., 1983. A revision of the lower Cretaceous stratigraphy of Lebanon. *Geologische Rundschau*, 72 (1) 377-388.
Walley, C.D., 1997. The Lithostratigraphy of Lebanon: A review. *Leb. Sc. Bull.,* 10(I).
Walley, C.D., 1998. Some outstanding issues in the geology of Lebanon and their importance in the tectonic evolution of the Levantine region. *Tectonophysics*,.
Walley, C.D., 2001. The Lebanon Passive Margin and the evolution of the Levantine Neo-Tethys. In Cavazza W., Robertson, A. H. F., and Ziegler, P. (Eds.), 2001. Peri-Tethys Memoir 6: Peri-Tethyan rift/ wrench basins and margins. *Mémoires du Museum National d'Histoire Naturelle*, Paris, pp. 407-420.
Wood, B.G.M., 2001. Intraplate primary and subsidiary basin formation and deformation: An example from central Syria. *Ph.D. Thesis, University of Oxford*, UK.