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Editorial Preface

It is my great pleasure to launch this inaugural issue of the Jordan Journal of Earth and Environmental Sciences (JJEES) with the intent of providing an international forum for the researchers and scientists of the various fields of Earth and environmental sciences to publish their scientific contributions and to disseminate their knowledge. The JJEES is an International Refereed Research Journal hosted by the Hashemite University and sponsored and approved by Jordan's Ministry of Higher Education and Scientific Research. The journal covers diverse areas of research and development in Earth and environmental sciences.

The coverage of the JJEES includes all new findings in all aspects of Earth and environmental sciences and or any closely related fields. The journal also encourages the submission of critical review articles covering advances in recent research of such fields as well as technical notes.

The Editorial Board is very committed to build the Journal as one of the leading international journals in Earth and environmental sciences in the next few years. With the support of the Ministry of Higher Education and Scientific Research and Jordanian Universities, it is expected that a valuable resource to be channeled into the Journal to establish its international reputation.

We have received a good response to the Previous issue of JJEES from scientists and researchers in Jordanian universities. I am pleased by this response and proud to report that JJEES is achieving its mission of promoting research and applications in Earth and environmental sciences. In this issue, there are five interesting papers dealing with various aspects of Earth and environmental sciences.

I would like to thank all members of the editorial board and the international advisory board members for their continued support to JJEES with their highly valuable advice. I would like also cordially thank the manuscript's reviewers for providing valuable comments and suggestions to the authors that helped greatly in improving the quality of the papers. My sincere appreciation goes to all authors and readers of JJEES for their excellent support and timely contribution to this journal.

The editorial board of JJEES and me, are looking forward to receiving your valuable scientific contributions. Your support and continued contribution would be highly appreciated.

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Diurnal and Seasonal Variation of Air Pollution at Al-Hashimeya Town, Jordan

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Abstract

This study aimed at using the statistical methods to assess air quality at Al-Hashimeya town in Zarqa Governorate. Three main sources at Al-Hashimeya are contributing to air pollution; Jordan Petroleum Refinery, Al-Hussein Thermal Power Station, and Assamra waste water treatment plant. Reports and data relating to pollution in al-Hashimeya were collected from different sources that measured the level of pollution in this area during spring season of the year 1992. Sets of data were processed, using statistical analysis. The results of the study indicated that Jordan Petroleum Refinery and al-Hussein Thermal Power Station were the two main sources of SO₂ because of the combustion of fuel that contains sulphur and SO₂ concentration that violated Jordanian standards. The study also showed that Assamra Station was the main source of H₂S and its concentration had exceeded the Jordanian standards throughout the monitoring months. CO and NO_x concentrations were within Jordanian standard. Ozone was in violation of Jordanian standards in more than 90% of the field measurements. Examination of the levels of TSP has shown that they exceeded the national standards with different degrees. Weather conditions (air Temperature, wind speed, rainfall, wind direction, cloud and relative humidity) have contributed to the high levels of air pollution.

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Keywords: Statistical Analysis; Air Pollution; ANOVA; SO₂; TSP; CO.

1. Introduction

In the last 200 years, or so, the growth in the world population and the industrial revolution has resulted in an increased demand for energy. Until now these energy requirements have been supplied largely by the combustion of fossil fuels, the plant's resources of conventional carbonaceous fuel, coal, and oil, have been used for heating purposes, power industry, transport and synthesis of chemicals. The by-products of these operations (particulates, the oxides of carbon, nitrogen and sulphur) have been emitted to the atmosphere in enormous quantities (Reida and John, 1988). Air becomes polluted when it contains substances in quantities that could harm the comfort or health of both humans and animals, or could damage plants or materials. These substances are called air pollutants and can be solid particles, liquid droplets or gases, and they occur naturally or as a result of human activity (Seinfeld, 1985).

Al-Hashimeya area is located north to Zarqa city about 35km northeast to Amman. This town is the most polluted city in Jordan; the air pollution has resulted from many factories and companies in the area, most important of which are Jordan Petroleum Refinery, al-Hussein Thermal Power Station, and Assamra wastewater treatment plant.

Different studies have been performed to understand source and level of air pollution in Al-Hashimeya. Most studies are restricted to water and soil. This study aims to use statistical analysis to give both qualitative and quantitative information about air pollution for the primary study for Al-Hashimeya during spring season in the year 1992, and to determine the impact of pollution controlling parameters (wind speed, wind direction, temperature, rainfall, solar radiation and relative humidity) on the behaviour of noxious gases in this town.

2. Methodology

2.1. Study Site

Al-Hashimeya area is located north of Zarqa city, 35km northeast of Amman. It is bounded by Longitude 36° 04' to 39° 09' east and Latitude 32° 04' to 32° 10' north (Figure 1). This town is the most polluted city in Jordan. The air pollution has resulted from many factories and companies in the area. Potential air pollution sources include, Jordan Oil Refinery, Khirbit Al-Samra Waste water treatment plant and Al-Hussein Thermal Power station. These sources are called "Triangle of Pollution". And every one of these has a different impact on air quality. A semi-arid Mediterranean type climate is dominant in Al-Hashimeya town which is characterized by hot and dry conditions in summer and lack of rain in winter. The average annual rate of rainfall is 142 mm. The low precipitation rates worsen the air quality in Al-Hashimeya because rain is natural

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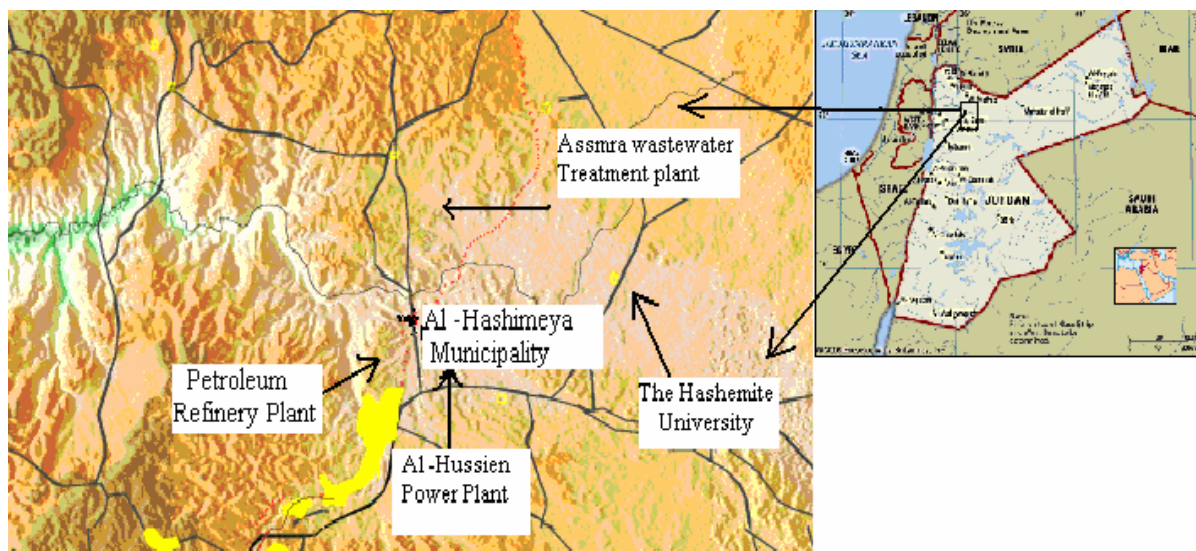


Figure 1. the Location of the Study Area.

processes that help washing out soluble substances from the air (Shehadeh and Noaman, 1991).

2.2. Data Collection

There have been several studies conducted by the Royal Scientific Society (RSS) and the Ministry of Environment to monitor basic pollutants in the area during 1992 (Table 1 and Fig.1). Instruments installed in the monitoring sites sample ambient air continuously and analyze it automatically, (Table 2 illustrate the instruments).

2.3. Preparing for Data Analysis

The yearly mean concentration of seven criteria pollutants PM_{10} , TSP, CO, NO_x , SO_2 , H_2S and Pb was used obtained from unpublished sources (RSS). Missing values were substituted. If the value was missing, for example, for a particular year, then it was substituted by taking the average of the preceding and succeeding years. This was done to preserve the seasonal patterns (as opposed to the effect of the procedure of substituting by the annual average.).

2.4. Statistical Methods

A personal computer was used to deal with data, using the statistical package (SPSS) version 11 and JMP and JMP IN Software version 4. The descriptive statistics of the variables: Mean, standard deviation, median and others of dependent variable were calculated, student t-test detect for significant between pairs of a variable ($p < 0.05$) unpaired data, One-way-ANOVA and Two-way ANOVAs were used to results.

Table1. Monitoring sites and their position from pollution sources in Al-Hashimeya.

Monitoring sites	Distance and direction of station from pollution sources
IBN EL Anbary School	6 km south west from SWTP 0.5 km north from HTPS 1.5km east from JOR
UM SOLEH	3 km from al hashymia town
THERMAL PLANT	5.5km southwest from SWTP 0.5 km south /southeast from HTPS 2km southeast from JOR
ELEMENTARY SCHOOL	4 km west from SWTP
SECONDARY SCHOOL	1 km northeast from JOR
ELECTRICAL TRAINING CENTER	0.5 km south from HTPS
HASHIMYEH MUNICIPALITY	Main highway of Irbid- Al hashymia-Zarqa
POLICE STATION/ZARQA	Main highway Zarqa Amman
PROJECT SITE	2km south east from SWTP 2 km north from HTPS 2km northeast from JOR
E. SCHOOL/ KHERBEH	2 km from south east from SWTP 6.8 km from northeast HTPS 7 km northeast from JOR
UM SHURYK	2 km south /southwest from SWTP 2.5 km north from HTPS 3km from northeast JOR

3. Result

3.1. Univariate Statistical Analysis

The first step in the data analysis involved the computation of basic statistics (e.g. Minimum, Maximum, Mean, Medians and Standard deviation as shown in (Table 3). These statistics are useful in the description of the distribution and to know the degree of pollution in the air. The concentrations of pollutants were compared with standard values recommended by WHO (Table 4).

Table 2. Instruments and their uses.

Instruments name	USES
Sulphure Dioxide Analyser UV-Flourescence	Analyse Sulphure Dioxide continuously
Hydrogen Sulfide Analyser UV-Flourescence	Analyse Hydrogen Sulfide continuously
Carbon Monoxide Analyser Non- Dispersive Infrared	Carbon Monoxide continuously
High Volume Sampler with Selective PM10 Inlet, Gravimetric.	Collect of PM10
Portable Calibrator Permeation Oven.	Calibrate instruments of pollutants measurement.
Wind Recorder Mechanical.	Measured of wind direction and wind speed.

Table 4 . Monthly average of pollutants and no. of exceeding according to WHO standard for 1992.

Monthly average of pollutants and no. of exceeding	WHO Standard	Month			Monthly average
		March	April	May	
Average monthly of SO ₂ (ppm)	0.047	0.059	0.071	0.056	0.062
Number of exceeding		13	17	16	16
Average monthly of TSP ($\mu\text{g}/\text{m}^3$)	120	183.25	169.7	221.8	176.6
Number of exceeding		4	8	12	8
Average monthly of H ₂ S (ppm)	0.006	0.006	0.006	0.007	0.0063
Number of exceeding		12	6	15	11
Average monthly of O ₃ (ppm)	0.06	0.07	0.06	-	0.065
Number of exceeding		28	18	-	23

3.3. Diurnal and Monthly Variation of Hydrogen Sulphide (H₂S)

The Concentrations of H₂S for all monitoring days ranged from 0.002 -0.030 ppm with mean of 0.0064 ppm and standard deviation of 0.004. This average exceeds WHO standards. Royal Scientific Society (RSS) recorded 33 violations of the standards in 88 days, with 28% of all samples. The Average Concentrations of H₂S in May was 0.007 ppm with 15 violations, i.e., 50% of the total samples. This average decreased in March to 0.006 ppm with 12 violations that gave rise to 43% of the total, and this monthly average is the same as in April but with about 6 days, (Table.3).

3.4. Diurnal and Monthly Variation of Ozone (O₃)

The Concentrations of O₃ vary between 0.0 -0.65 ppm with a mean value that equals 0.074 ppm and a standard deviation of about 0.082. This average exceeds WHO standards. It violated the standard 46 times out of 51 days, which means that the violation is 90% from all the samples (Figure 2).

3.2. Diurnal and monthly variation of Sulphur dioxide (SO₂)

The average of SO₂ concentrations at Al- Hashimeya region registered was 0.062 ppm. This average exceeded the Jordanian standards and the directions of WHO for 46 days out of 80 sampled days. The highest monthly average for SO₂ was 0.071 ppm for April. The average was yet similar to March and May 0.059ppm. This rise of the concentrations in April is due to the low air temperatures, humidity, lack of rainfall, and the lack of Ozone (O₃). This helps a lot in the process of SO₂ removal through oxidization. It was noted that the levels of concentrations were not affected during weekends and other formal vacations.

Table 3. Minimum ,Maximum ,Mean and St. Dev. of pollutants at Al -Hashimeya in 1992

Variable	Minimum	Maximum	Mean	St. Dev.	Number of violation (Days)
SO ₂ (ppm)	0.00	1.01	0.111	0.197	87
H ₂ S (ppm)	0.002	0.030	0.0064	0.0042	88
O ₃ (ppm)	0.00	0.650	0.0743	0.082	53
TSP(mg/m ³)	1.90	500	160.67	91.07	52

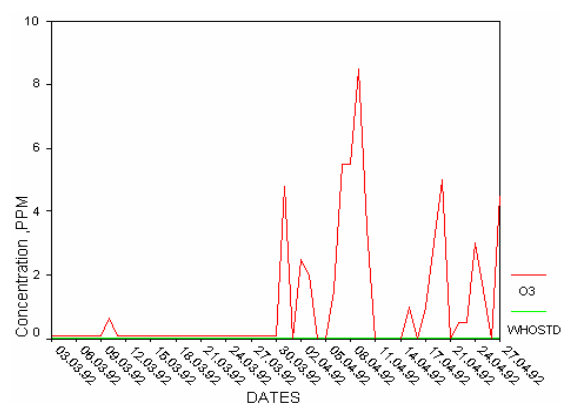


Figure 2. Concentration of O₃ and WHO Standard at Al-Hashimeya in 1992.

The Average Concentrations of O₃ in March was 0.07 ppm in 28 days ,i.e., 100% , but the concentration decreased in April to 0.06 ppm , 18 sample exceeded standards, that mean 78% of the samples in this month .The high concentration of O₃ might correspond to increases in sunlight that helps nitrogen oxides and

volatile organic compounds reacting with each other to form photochemical oxidants (also known as photochemical smog) of which ozone is the principal component. Whereas the values ranged in April between 0.030 - 0.084 ppm, (Table 3).

3.5. Diurnal And Monthly Variation of Total Suspended Particles (TSP):-

The monthly average of Total Suspended Particles (TSP) exceeded the 120 $\mu\text{g}/\text{m}^3$ ppm WHO Standard days out of 31 day i.e. 77%. The average concentrations of TSP in May reached 221.8 $\mu\text{g}/\text{m}^3$ ppm with 12 days violations, 92 %, this is due to low wind speed and humidity and west wind direction. In April, the average exceeded WHO standards with a mean value of about 169.7 $\mu\text{g}/\text{m}^3$ ppm with 8 days violation, i.e., 80%. But in March the average monthly of TSP reached to 138.25 $\mu\text{g}/\text{m}^3$ ppm with 4 days that reach ed to 50% of all the samples (Figure 3). The average exceeds WHO standards with a mean value of about (84.4 $\mu\text{g}/\text{m}^3$) with 37 days violate from all the samples.

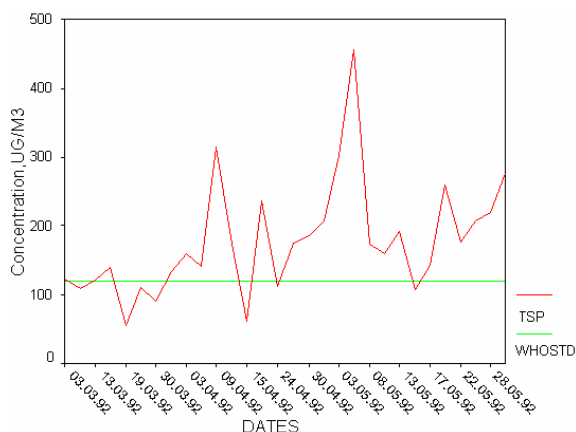


Figure 3. Concentration of TSP and WHO Standard at Al-Hashimeya in 1992.

The highest monthly average of TSP is that of May that ranges from 108 – 455 $\mu\text{g}/\text{m}^3$ ppm, and the lowest average was found in March which ranged from 56 – 352 $\mu\text{g}/\text{m}^3$, and this concentrations exceeds WHO standards. In April, it was 62 – 316 $\mu\text{g}/\text{m}^3$. These percentages exceed the international standards. This is more obvious when we compare these results with Umm Soleh, 3kms far from the study area. Studies indicate that the percentage of concentrations reached one third of the total percentage i.e., 38% of the whole exceedings.

Figure (4) shows that the comparison of the TSP concentration in Ibn el-anbari (inside Al- Hashimeya area) and Um Suleh, (far 3Km west from Al- Hashimeya). TSP concentration in Ibn el-anbari is higher and exceeds to one-third, compared to Um suleh.

3.6. Diurnal and Monthly Variation of Carbon Monoxide (CO)

Levels of this gas were low at the observance period, where it didn't exceed WHO standards, 9 ppm i.e., 8 hours as an average in the light of the day where the highest concentration of this gas reached 5 ppm in April.

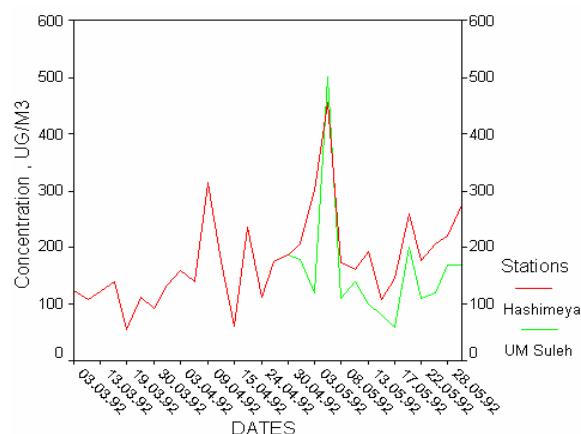


Figure 4. Variation in TSP levels at Al- Hashimeya and Um Suleh in 1992.

4. the Factors Affecting the Concentration of Air Pollutants At Al-Hashimeya

Meteorology plays a great role in influencing the air pollutants at Al-Hashimeya ,where the total explanation caused by these factors reach 43% of the percentage of pollution during spring season (March ,April and May).This percentage varies from 22% in March to 52% in April and 21% in May.

4.1. Meteorological Impact on SO2 Concentration:-

(Table 5) shows the most important metrological factors that influenced SO₂ concentration in the air. These factors explained 37% of dissimilarity in March, 84% in April and 29% in May.

Table 5. Metrological Factors affect on the CONCENTRATION of SO₂ at Al-Hashimeya in 1992.

Month	Variables	R ²	R ² Adjusted	Correlation coefficient	Significant level
March	Rainfall	0.37	0.37	-0.61	0.01
April	Temperature	0.58	0.58	-0.76	0.01
	Wind Speed	0.14	0.73	0.67	0.01
	Wind direction	0.08	0.81	0.34	0.05
	Cloud	0.02	0.84	0.47	0.01
May	Wind Speed	0.29	0.29	0.54	0.01
All Months	Wind Direction	0.21	0.21	0.43	0.01
	Relative Humidity	0.16	0.37	0.39	0.01

4.2. Metrological Impact on H2S Concentration:-

The most important meteorological factors that affected the H₂S concentration in spring was Wind Direction. Calm winds are prevailing in Al -Hashimeya region, 38.6%. Also West winds blow on the region in 31.8%, south winds with 18.2%. The Eastern winds blow reached 2.3%, southeast reached 4.5%, southwest 2.3% and northwest reached 1.1%.

Clearly, winds play a big role in affecting the percentage of H₂S gas, 14% of distraction in H₂S value with -0.32 negative correlated with coefficient value are explained at 99% reliability (Table 6). This relation is mainly due to the increase in the percentage of calm winds, and west winds, which increased the air pollution level in the study area, wind in carrying these pollutants from their resources (Petroleum Refinery and Al-Sammra station) to the sampling location.

It is clear that the speed of the wind plays a big role in increasing the H₂S concentrations in March. It explains 31% of the dissimilarity of the gas values with a negative correlation of -0.56 at the 99% significance level. i.e., when the wind speed is decreased, the level of air pollution is increased in Al-Hashimeya.

The average relative humidity in Al-Hashimeya is approximately 81.3% for the month of April. Humidity is an important factors that decreases the H₂S concentration. It explains 27% of the dissimilarity in the gas value with a negative correlation -0.52, at 99% of confidence. When there is an increase in relative humidity in the atmosphere, the concentration value decreases. The negative correlation is attributed to the role of humidity in increasing the chemical interactions for the gases and water vapour in order to form droplets, as well as forming the photochemical smog.

Table 6. most important metrological factors that affect the increase of H₂S in the air.

Month	Variables	R ²	R ² Adjusted	Correlation Coefficient	Significant level
March	Wind Speed	0.31	0.31	-0.56	0.01
April	Relative Humidity	0.27	0.27	-0.52	0.01
	solar radiation	0.06	0.33	-0.37	0.05
All Months	Wind Direction	0.14	0.14	-0.32	0.01

4.3. Metrological Impacts on Ozone Concentration

Humidity is considered among the meteorological factors that influences O₃ concentration. It explains 22% of the dissimilarity in the gas value with a negative correlation -0.48, at 99% of confidence (Table 7). When there is an increase in the relative humidity, the O₃ concentration decreases, the negative correlation is attributed to the role of humidity in increasing the chemical interactions for the gases and acid rain as well as forming the photochemical smog.

Table 7. most important metrological factors that affect the increase of O₃ in the air.

Month	Variables	R ²	R ² Adjusted	Correlation coefficient	Significant level
March	Relative Humidity	0.22	0.22	-0.48	0.01
May	Relative Humidity	0.22	0.22	-0.47	0.01

4.4. Metrological Impact on TSP Concentration:-

The main factors affecting TSP are temperature and clouds (Table 8). The mean average of temperature at Al-Hashimeya is approximately 17.3 C° with a maximum value of 29.30 C° and a minimum of 7.2C°. Thus such temperatures have an effect on on the concentration of TSP. It therefore explains 22% of the dissimilarity in the values of this gas with a negative correlation coefficient -0.50. The reason behind the negative correlation is that high temperatures enhance convection currents, which helps in good air mixing and reducing TSP concentration. Low air temperatures results in stable atmosphere and poor air quality.

The amount of clouds affects the percentage of TSP concentration; it explains 14% of dissimilarity in the values of TSP at a positive correlation of 0.37 at 99%.

Table 8: Metrological Factors that Affect the Increase Of TSP in the Air.

Month	Variables	R ²	R ² Adjusted	Correlation coefficient	Significant level
March	Temperature	0.19	0.19	-0.44	0.01
May	Cloud	0.14	0.14	0.37	0.05
All months	Temperature	0.22	0.22	-0.50	0.01

5. Discussion

It is observed that the main sources of Sulphur dioxide emissions in Al-Hashimeya town are Jordanian Petroleum Refinery and Al-Hussein Thermal Power station due to burning heavy fuel oil with high Sulphur content. It was also noticed that the areas located north, northeast and southeast are mainly affected by SO₂ emissions from the refinery, as Al-Husain station's influence is low in comparison with the refinery because the prevailing winds in Al-Hashimeya region are west headed. The study also showed that Assamra Station is the main source for the emanation of H₂S and the density of this gas has exceeded the Jordanian standards in this respect throughout the monitoring months whereas the levels of nitrogen oxides and CO concentrations are low in the ambient air in this town, but for TSP the concentration is high and it exceeds the WHO standards.

Results have proved that the high concentrations of TSP were attributed to the prevailing Khamasin winds, which is common in spring, especially in April and May, in addition to the high temperature and the low average of rainfall and low humidity, thus helping responding fugitive dust.

Temperature shows an inverse relation with most of the pollutants because of the role of the heat in warming up the surface of the earth by the oncoming radiation from the sun which strikes the earth and warms it, thus making the air that touches it warm and consequently reducing its density, so it expands and goes upward to be replaced by cold air and so on. This process increases the amounts of the up going air currents. When the horizontal and vertical air mixing processes increase, they reduce the concentration of the pollutants in it. Further, the decrease in temperature for some pollutants increases the production of some pollutants due to an increase in the

burning times and using of the central heating, which results in the increase of these pollutants like NO_x , SO_2 , CO. The relation of TSP with temperature is proportional, as the increase in temperature leads to generating more air currents and shaping vertical winds, thus causing dust and therefore TSP increases in the area. Humidity is low in Al-Hashimeya city. It's annual rate amount 65%. The process of humidity decrease leads to more concentrations of gas contaminations and suspended dust in the air, which results from Oil Refinery, Al- Hussien thermal power station and Al- Kherbh Al- Sammra.

The relation of relative humidity with the concentration of the pollutants is proportional relation, which could be attributed to the role of the humidity in causing the heat discrepancies as the increase of humidity in the atmosphere reduces the amount of solar radiation that reaches the earth, and when sunshine collides with these drops, then it absorbs these scattered drops in the surrounding atmosphere, so they start to evaporate and launch their embedded heat in the surrounding air, which contributes in forming heat variations where the air near to the surface of the earth is becoming colder than that in the upper parts, thus reducing the up going air currents and accordingly increasing the pollutants in the atmosphere.

6. Conclusion

The results have shown that the observed levels of air pollution exceeded the Jordanian standard for air quality and the study proved that the effect of meteorological factors play a great role in influencing the air with gases and dust in Al – Hashimeya area.

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Petrology and Geochemistry of the Metasediments of the Janub Metamorphic Suite, Southern Jordan: Implications for Geothermobarometry and Economic Potential

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Abstract

Petrographical and geochemical characteristics of the hornfelses and metaconglomerates of the Janub metamorphic suite have been examined to reveal their geothermobarometry and economic potential. The temperature of metamorphism attained by hornfelses ranges between 500°C and 545 °C with an average temperature of 522°C, while metaconglomerate may show a wider range between 300 °C to 600 °C with an average temperature 520 °C. Mineralogy of the metasediments indicates a low pressure type of metamorphism (< 4 Kbar). These conditions correspond to metamorphism equivalent to upper greenschist to lower amphibolite facies. The identified opaque minerals are ilmenite, magnetite and titanomagnetite. Sulphides are less abundant and include pyrite, cinnabar, pyrrhotite, sphalerite, galena and chalcopyrite.

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Keywords: Arabian-Nubian Shield; Janub Metamorphic Suite; Hornfelses; Metaconglomerates; Mineral Chemistry; Geothermobarometry.

1. Introduction

The Precambrian basement complex of Jordan is located at the northernmost extremity of the Arabian-Nubian Shield (ANS). The formation of ANS took place mainly during the Pan-African Orogeny 900-550Ma; (Kröner, 1985). This basement consists of igneous, sedimentary and metamorphic rocks; and is exclusively of Neoproterozoic age 550-800 Ma (e.g., Jarrar et al., 2003). These rocks are broadly divided into two broad lithostratigraphic divisions: the Aqaba and Araba complexes (McCourt & Ibrahim, 1990). The Janub Metamorphic Suite (JMS), which belongs to the Aqaba Complex, is the theme of this study (Fig. 1).

The study area is located in the southernmost corner of Jordan near the Jordan –Saudi Arabia border. The JMS is considered as one of the oldest suites together with Abu Barqa metasedimentary suite. McCourt & Ibrahim (1990) described Janub suite rocks as low grade metamorphic rocks, belonging to lower – middle greenschist facies. Characteristically, these are preserved as roof pendants and large xenoliths in Abu Jadda monzogranite (Yutum suite). Most lithologies in this area are metasediments dipping to the north with an approximate E-W directed strike. Hassuneh (1994) divided the metasedimentary rocks in this area on the basis of petrographical and geochemical criteria into three groups:

a. Cordierite – biotite hornfels

b. Metaconglomerates.

c. Quartzo – feldspathic metasediments.

This study aims at revealing conditions of formation in terms of pressure, temperature, and the mineralogy and geochemistry of the opaque minerals to evaluate their economic potential

2. Analytical Techniques

The investigated rocks were analyzed using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) at the Institute für Geowissenschaften of the Technical University of Braunschweig, Germany for their major, minor, and trace elements. The Mineral separation was carried out at the Geology Department, University of Jordan.

Mineral analyses have been carried out by the third author on the Cameca SX100 microprobe at the Institute of Mineralogy, University of Stuttgart, Germany

3. Petrography

The first detailed petrographical description of Janub metamorphic suite was carried out by Rabba and Ibrahim (1988) and Hassuneh (1994). In the present study only two rock types were studied: namely hornfelses and metaconglomerates.

3.1. Pelitic Hornfelses

The investigated hornfelses are composed of biotite and quartz as major minerals and subordinate cordierite, sillimanite, K-feldspar, and amphibole. Chlorite occurs as

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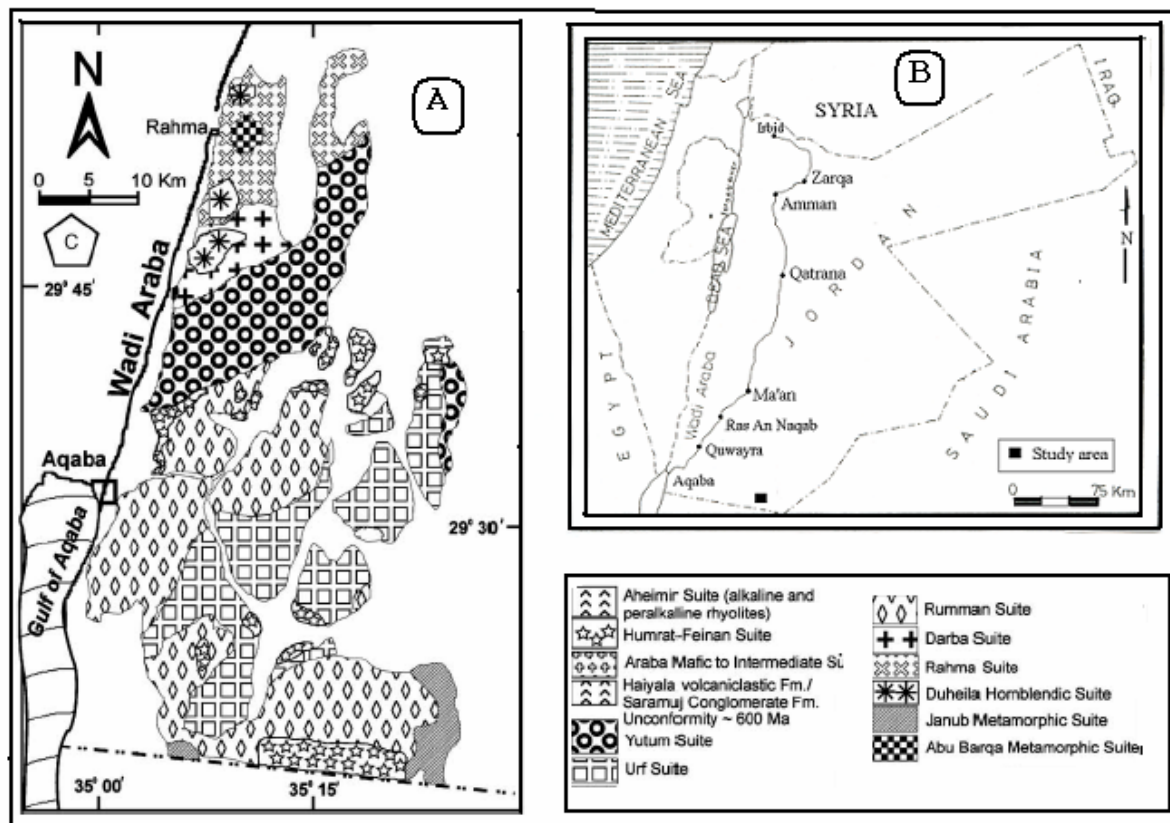


Figure 1. A. Location map of the principal suites of Aqaba Complex (after Jarrar et al., 2003), B. Location map showing the study area..

pseudomorphs after biotite. Accessory minerals are opaques and corundum.

The investigated rocks are characterized by preservation of some original sedimentary textures such as quartz granules and pebbles, phenocrysts and bedding planes. These features imply a lack of intense deformation during contact metamorphism (Hyndman, 1985).

Decussate texture (Fig. 2), Poikiloblastic and sieve textures (Fig. 3) are the most commonly encountered textures in hornfelses.

Most of the cordierite porphyroblasts in thin sections are anhedral, which together with the numerous inclusions indicate a rapid growth (Barker, 1990).

The occurrence of cordierite in Mg – rich rocks (low Fe/Fe+Mg ratio) of the bulk composition of hornfelses indicate low pressure and low water content (Yardly, 1989). Cordierite may form at low pressure in pelitic rocks according to the following reaction:

Chlorite + Muscovite → Cordierite + Biotite + Quartz + H₂O (Hyndman, 1985)

3.2. Metaconglomerates

The mineralogy of the metaconglomerates varies as a function of their original mineral content and texture since they were derived from different sources. The coarse-grained varieties of these rocks are mainly of quartzofeldspathic, granitoid and arkosic lithologies, with grain size ranging between 2mm to 10mm. The dominant minerals in these rocks are quartz, biotite, K-feldspar, plagioclase, amphibole, chlorite and opaques. Minor minerals include: epidote, muscovite, secondary clay minerals, garnet and tourmaline.

Granoblastic (Fig 4), poikiloblastic, and cataclastic textures are very common. The latter is characterized by wavy extinction, mortar textures, fracturing, and elongated grains (Fig 5). Furthermore, most of the samples consist of quartz, K-feldspar, plagioclase, biotite, chlorite pseudomorphs after biotite, amphibole and opaques. According to Hassuneh (1994) this mineral assemblage is characteristic for quartzofeldspathic rocks.

In the two metasedimentary lithologies, the opaques vary in size (0.01 up to 0.25mm), while in the metaconglomerates they occur as small grains distributed in the whole sample or concentrated in vein-like aggregates; in hornfelses opaques are less abundant. In most of the samples the opaque granules are associated with mafic minerals.

4. Geochemistry

The chemical composition of the investigated rocks is presented in Tables (1) and (2).

Several plots have been used to reveal the petrological evolution of the suite and to help make inferences regarding the protolith of the metamorphic rocks. The metaconglomerates show a negative relationship between SiO₂ vs. MnO, Fe₂O₃, TiO₂, MgO, Al₂O₃, and CaO; a positive correlation between SiO₂ vs. K₂O, and a slightly positive correlation between Na₂O with SiO₂ (Fig 6). These trends reflect the relationships between the elements in the source rocks and/or the behaviour of elements during weathering.

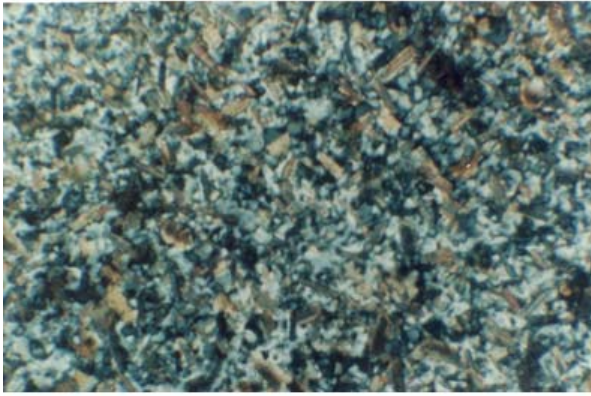


Fig. 2



Fig. 3

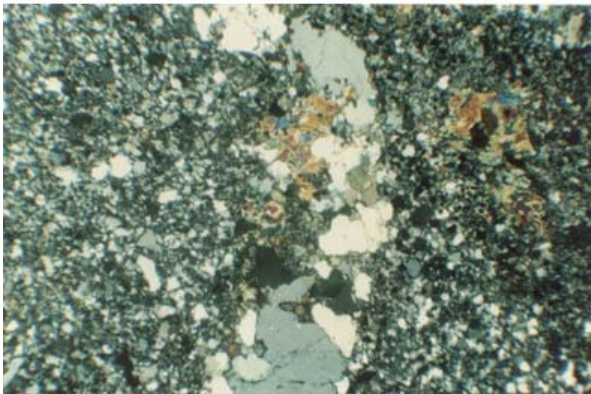


Fig. 4

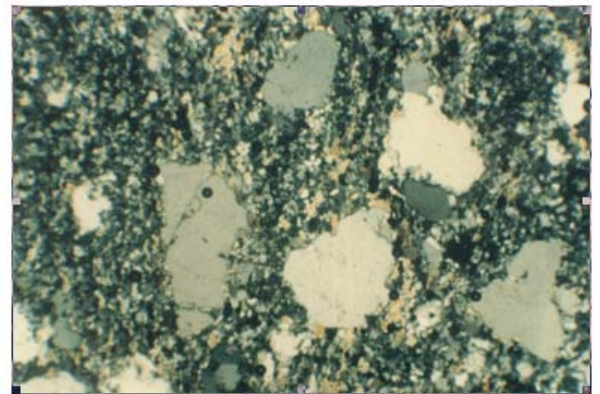


Fig. 5.

Figures (2-5): Figure 2. Decussate texture: prismatic grains of biotite (brown) distributed randomly around quartz grains (white to gray). (Mag. 250, XPL), Figure 3. Cordierite porphyroblasts (at the center to the top right) with numerous inclusions of biotite forming sieve texture. (Mag. 125, XPL), Figure 4. Granoblastic quartz filling a vein, clots of small crystals of amphiboles can also be seen. Note the differences in the grain size of quartz. (Mag. 125, XPL), Figure 5. Relics of large grains of quartz surrounded by small grains of amphibole, and quartz, note the fracturing of relic grains. (Mag. 50, XPL).

The resistant minerals such as quartz are retained as framework components while the other rock fragments of less resistive composition have gone into the matrix, therefore most of Fe_2O_3 , MgO and CaO are in the matrix (Naqvi et al., 1988). The negative correlation of these oxides with SiO_2 supports this conclusion and reflects a decrease in the unstable component (e.g. rock fragments and feldspar) with an increase in mineralogical maturity (Gu et al., 2002). The positive correlation between K_2O vs. SiO_2 and scatter between on the Na_2O vs. SiO_2 diagram reflects the abundance of felsic rock fragments in the metaconglomerates.

The hornfelses display the same features as metaconglomerate with the exception of CaO (Fig (7)). The positive correlation of CaO with SiO_2 reflects the preference of CaO to reside in the fine-grained matrix during sedimentary processing (Naqvi et al. 1988). The high negative correlation between SiO_2 with other major elements reflects similarity of the matrix in sedimentary rocks such as greywackes. (Naqvi et al., 1988). Saupe and Vegas (1987) have used the K/Al vs. Na/Al and $(\text{Fe}+\text{Mg})/(\text{Al}/\text{Na})$ vs. $\text{K}/(\text{Al}-\text{Na})$ to classify clastic sedimentary rocks into shale, greywacke and arkoses. The hornfelses fall in the shale field while the most of metaconglomerates fall in greywacke and to a lesser degree in arkoses field (Fig. 8).

5. Mineral Chemistry

Mineral chemistry is used to constrain $P - T$ conditions of metamorphism and shed light on the origin of the protolith of the investigated rocks. The chemical data of the analyzed minerals are presented in Tables 2 to 6.

5.1. Pyroxenes

The pyroxenes are essential minerals in most mafic to ultramafic igneous rocks and high-grade metamorphic rocks. Pyroxene classification scheme after Morimoto et al., (1988) has been used to divide the analyzed pyroxenes into:

- Ferroan diopside; and
- Sub calcic magnesium rich augite. Table (2).

Clinopyroxenes appear only in some samples of the metaconglomerate.

$X_{\text{Mg}} = \text{Mg}/(\text{Mg} + \sum \text{Fe of pyroxenes})$ ranges between (44.9 – 73.7) with average of 63.7; and the (Wo) content ranges between 26.7 and 46.9.

5.2. Feldspars

Feldspars are the most abundant mineral group in the Earth's crust and form about 50% by weight of both continental and oceanic crust. The compositional triangle of feldspars has been used to divide the analyzed plagioclase into oligoclase and andesine. Plagioclase in metamorphic rocks becomes anorthite-rich with increasing

Table 1. Major (in wt %) and trace (in ppm) elements concentrations and elements ratios for the metaconglomerate and the hornfels rocks.

Sample	A1	A5	A7	A8	A9	A10	A11	A12	A13	A14	A20	A22	A24	A30	A31	A38	A40	Z28	Z29	Z30	Z31	Z32	Z33	54x		
SiO ₂	64.2	66.74	72.14	64.05	64.2	60.27	71.62	65.22	62.5	67.03	69.05	56.9	66.48	63.89	60.29	70.61	66.52	64.62	58.42	58.51	58.5	64.28	62.36	60.91		
Al ₂ O ₃	14.32	15.16	13.45	14.81	13.26	16.27	14.07	15.68	15.33	14.43	14.84	18.46	13.89	14.45	15.75	13.94	16.35	15.2	14.51	13.86	15.93	14.5	15.87	15.65		
Fe ₂ O ₃	2.89	3.35	1.98	6.06	5.16	7.16	2.68	5.42	5.35	4.97	2.32	5.57	3.59	6.8	7.87	1.34	6.39	6.05	7	6.16	6.69	5.76	6.79	7.8		
MgO	1.4	1.48	0.46	1.48	0.97	2.71	0.71	2.43	1.73	1.34	1.04	2.5	2.24	2.61	2.33	0.29	2.63	2.48	2.92	2.62	2.8	2.38	2.88	3.55		
MnO	0.06	0.08	0.08	0.16	0.23	0.15	0.08	0.07	0.06	0.06	0.06	0.09	0.08	0.08	0.21	0.02	0.08	0.11	0.1	0.12	0.09	0.09	0.14	0.17		
CaO	1.58	2.92	2.41	4.25	6.54	3.32	2.61	3.96	3.82	3.35	2.98	4.16	2.11	2.22	1.69	0.36	1.61	0.94	1.21	1.4	2.17	1.8	1.08	1.84		
TiO ₂	0.55	0.43	0.39	0.97	0.45	1.26	0.43	0.61	0.69	0.64	0.4	0.76	0.66	0.97	1.06	0.28	0.79	0.74	0.76	0.79	0.84	0.7	0.83	0.77		
Na ₂ O	3.3	4.11	2.62	4.18	1.99	2.78	2.8	3.49	3.73	3.14	3.25	4	3.77	3.51	4.07	4.41	2.77	1.99	2.29	2.31	3.43	2.43	2.2	2.13		
K ₂ O	4.12	1.58	3.64	2.44	2.67	3.71	3.47	2.24	2.88	2.32	2.58	2.17	4.09	3.67	4.23	5.02	2.63	2.91	2.54	2.58	2.41	2.17	2.23	1.79		
P ₂ O ₅	0.17	0.09	0.11	0.26	0.16	0.29	0.12	0.12	0.14	0.17	0.07	0.29	0.17	0.22	0.26	0.03	0.15	0.17	0.17	0.18	0.28	0.52	0.19	0.16		
Total	92.6	95.94	97.27	98.66	95.63	97.91	98.59	99.23	96.22	97.44	96.57	94.91	97.07	98.42	97.76	96.31	99.93	95.22	89.93	88.53	93.14	94.64	94.56	94.78		
Trace elements (ppm)																										
Ba	1400	770	2041	572	1379	1249	1197	826	1004	302	1416	517	1068	818	627	778	453	663	448	532	631	554	631	423		
Th	11	9	10	5	9	7	9	5	6	4	12	5	12	6	8	12	5	5	5	5	6	6	6	6		
U	5	2	3	2	4	2	3	2	2	2	4	2	4	2	3	4	2	2	1	2	2	2	2	2		
Nd	37	47	50	32	48	44	53	22	28	22	31	21	30	31	46	35	25	25	23	26	31	39	28	27		
Sm	7	10	10	7	10	9	10	5	6	5	6	5	6	7	10	7	6	5	5	6	7	9	6	6		
B	65	46	23	103	88	123	33	88	89	71	37	99	55	120	135	19	98	99	116	106	117	100	124	129		
Cd	1	1	-2	2	0	3	-1	1	1	1	107	2	0	2	2	2	2	2	0	0	4	3	2	3		
Cr	21	11	1	91	10	72	9	71	69	69	16	71	104	43	37	14	118	112	39	32	142	120	139	144		
Cu	6	10	0	158	2	0	28	39	182	10	205	1	17	29	5	16	11	32	49	43	8	26	12	31		
Ni	17	9	10	36	12	31	12	27	21	25	608	23	42	24	20	13	37	41	164	169	50	44	50	50		
Pb	264	210	336	222	291	180	239	177	186	235	31	193	192	182	200	283	202	195	151	123	141	159	160	182		
Sr	486	665	677	457	603	540	556	489	435	162	54	452	455	280	199	68	173	165	108	109	373	209	168	204		
V	90	49	36	149	50	148	41	111	127	104	174	139	102	148	142	28	131	129	78	53	157	145	156	156		
Zn	46	52	42	62	45	98	39	28	32	37	41	52	42	45	169	27	44	75	175	195	41	64	60	105		
Zr	94	226	316	174	255	215	306	115	144	147	174	164	157	248	305	210	189	177	175	195	193	191	172	183		

metamorphic grade (Laird and Albee, 1981). In sample (A9) the plagioclase is of labradorite (An= 50%) and anorthite (An=97%) composition. The plagioclase of this sample is most probably of relict igneous origin.

Barium in orthoclase ranges from zero to 0.81 wt. % with an average of 0.38 due to substitution of barium for potassium. The anorthite content of the plagioclase in hornfelses ranges from 27 – 32 % and in metaconglomerates from 1 to 34 %, with the exception of the above mentioned sample (A9). Table (3)

5.3. Mica

Micas are a major group of phyllosilicates, common in igneous, metamorphic, and sedimentary rocks. All micas in the samples with the exception of X51 are biotites. This sample was taken from a rhyolitic dyke and contains muscovite, table (4).

Biotite is iron-rich with $X_{Mg} = (Mg/(Fe+Mg))$ ranging from 29 to 48 and averaging 39 for all samples. Ti ranges between 0.05 – 5.93 wt. % with an average value of 3.03; and Ba ranges between 0 – 0.19 wt. percentage with an average value of 0.08. This indicates that most barium in

the samples was substituted for potassium in the feldspar rather than biotite. Al^{IV} and probably Al^{VI} and Ti increase in biotite with increasing metamorphic grade (Laird and Albee, 1981).

The X_{Mg} of the biotites in sample X54 ranges between 29 and 34, almost the same as the X_{Mg} of the whole rock for this sample, which implies that biotite is the only Mg-bearing mineral in this sample. On the other hand, the X_{Mg} of the whole rock of A9 = 16.2, while the X_{Mg} value of biotite in A9 equals 48.

The X_{Fe} ratio of biotite mainly depends on oxygen fugacity, therefore at elevated oxygen fugacity (f_{O_2}), biotite becomes rich in Mg (Wones and Eugster, 1965). The elevated iron content of the biotite reflects low oxygen fugacity during their formation.

5.4. Titanite (CaTiSiO₅)

This mineral is composed of (26.7 – 28.2%) CaO, (35.09 – 38.5%) TiO₂ and (30.2 – 31.1%) SiO₂ with minor amounts of Al, Fe, Mn, and Cr. Table (5)

Table 2: The chemical composition and formulae of pyroxenes.

Sample. No.	A9 ₁	A9 ₂	Hc ₅
	Wt%	Wt%	Wt%
SiO ₂	51.062	45.413	50.927
TiO ₂	0.048	0.437	0.187
Al ₂ O ₃	1.198	6.798	3.933
Cr ₂ O ₃	0.029	0.021	0.017
FeO	8.706	15.197	10.059
MnO	1.879	1.512	0.970
MgO	12.336	12.390	16.563
CaO	21.719	11.849	12.516
Na ₂ O	0.163	0.703	0.494
K ₂ O	0.318	0.318	0.318
TOTAL	97.458	94.638	95.984
No Oxygens	6	6	6
Si	1.974	1.822	1.945
Al	0.026	0.178	0.055
Al	0.028	0.143	0.122
Fe(iii)	0.034	0.117	0
Cr	0.001	0.001	0.001
Ti	0.001	0.013	0.005
Fe(ii)	0.247	0.0388	0.322
Mn	0.062	0.051	0.031
Mg	0.711	0.741	0.943
Ca	0.899	0.509	0.512
Na	0.012	0.055	0.037
K	0.016	0.016	0.015
TOTAL	4.010	4.034	3.988
X Mg	58.6	44.9	62.2
Wo	45.78	27.36	27.76
En	36.18	39.82	51.1
Fs	17.41	29.88	19.16
Ac	0.62	2.94	1.98

5.5. Opaques

Most of opaque phases in the analyzed samples are titanium and iron oxides and minor quantities of sulfides especially pyrite (Table 5)

5.5.1. Ilmenite (Fe Ti O₃)

Ilmenite is composed of (35.5 – 51.1%) TiO₂, (35.7 – 54.7%) FeO, (1.98 – 12.5) MnO, and minor amounts of Cr. The formula can be expressed as (Fe, Mg, Mn) TiO₃ with limited Mg and Mn substitution for iron

5.5.2. Pyrite (FeS₂)

The iron content of pyrite in X51 sample ranges between 47.15 %– 49.66 % with an average value of 48.25 %. In general, pyrite is composed of 46.6 % Fe and 53.4 % S and minor amounts of Co, Ni. (Klein, 2002).

Table 3: The chemical analyses and formulae for the feldspar. The formulae were calculated on the bases of 8 oxygen's.

Sample	X54	b	A9	X51	HC-M
Na ₂ O	8.65	6.20	6.58	0.59	1.56
SiO ₂	58.35	58.23	59.48	44.82	65.91
Al ₂ O ₃	24.44	27.40	24.73	34.11	18.81
MgO	0.00	0.02	0.44	0.37	0.01
K ₂ O	0.06	0.28	2.85	9.82	14.01
CaO	5.81	9.34	2.62	0.07	0.07
TiO ₂	0.00	0.06	0.01	0.33	0.00
FeO	0.27	0.18	0.53	1.97	0.02
BaO	0.00	0.02	0.00	0.00	0.30
Summe	97.60	101.72	97.23	92.07	100.68
Na	0.768	0.530	0.584	0.057	0.138
Si	2.671	2.569	2.722	2.247	3.000
Al	1.318	1.425	1.334	2.016	1.009
Mg	0.000	0.001	0.030	0.028	0.001
K	0.004	0.016	0.166	0.628	0.814
Ca	0.285	0.442	0.128	0.004	0.003
Ti	0.000	0.002	0.000	0.012	0.000
Fe	0.010	0.006	0.020	0.082	0.001
Ba	0.000	0.000	0.000	0.000	0.005
Summe	5.056	4.991	4.984	5.074	4.971
Albite %	72.679	53.653	66.466	8.309	14.370
Orthoclase %	0.346	1.599	18.936	91.151	84.745
Anorthite %	26.975	44.715	14.596	0.529	0.335
Celsian %	0.000	0.033	0.002	0.011	HC-M

5.5.3. Magnetite

It is mostly composed of (88.7 – 93.5%) of total iron. Fe₂O₃ content ranges from 6.26 to 10.6%) and FeO content ranges from 79.6 to 87.5%.

5.5.4. Titanomagnetite

Titanomagnetites are mostly composed of (70.6 – 79.6) iron, (7.7 – 20.7) TiO₂ and minor amount of (0.72 – 3.47) MnO.

5.6. Amphibole

Amphiboles are an important group of minerals in a wide spectrum of igneous rocks from felsic to mafic end members. Further, they are major constituents in metamorphic rocks derived from basic igneous rocks and impure limestones.

Depending on Leake (1997), the amphiboles in the samples with formulas calculated on the basis of 23 of oxygens include: actinolite, richterite, magnesiohornblende, actinolitic hornblende, and subsilicic gedrite.

Most of the amphiboles in the investigated rocks are calcic amphiboles; this group is characterized by (Ca + Na)_B ≥ 1.34 and Na_B < 0.67 (Table 6)

Si vs. Mg / (Mg+Fe) diagram after (Leake, 1997) is used to classify the calcic amphibole. This figure shows

Table 4. The chemical analyses of biotite and their formulae calculated on the basis of 22 oxygen.

Samples	Hc 1	X54 ₄	A9	X51 _a
	Wt%	Wt%	Wt%	Wt%
SiO ₂	36.160	31.740	37.330	46.800
TiO ₂	2.490	2.370	2.080	0.050
Al ₂ O ₃	17.070	16.190	14.640	35.260
Cr ₂ O ₃	0.020	0.100	0.010	0.000
FeO	21.870	22.350	15.410	1.860
MnO	0.140	0.150	1.030	0.100
MgO	10.020	10.740	14.280	0.770
CaO	0.000	0.050	0.120	0.000
Na ₂ O	0.240	0.180	0.120	0.520
K ₂ O	7.930	5.940	8.560	10.570
BaO	0.110	0.130	0.170	0.060
TOTAL	96.050	89.940	93.750	95.990
Si	5.487	5.183	5.681	6.199
Al (iv)	2.513	2.817	2.319	1.801
T	8.000	8.000	8.000	8.000
Al (vi)	0.539	0.298	0.307	3.703
Ti	0.284	0.291	0.238	0.005
Cr	0.002	0.013	0.001	0.000
Fe(iii)	0.000	0.000	0.000	0.000
Fe(ii)	2.775	3.052	1.961	0.206
Mn	0.018	0.021	0.113	0.011
Mg	2.267	2.615	3.240	0.152
M	5.885	6.290	5.860	4.077
Ca	0.000	0.008	0.020	0.000
Na ***	0.071	0.057	0.035	0.134
K	1.535	1.237	1.662	1.786
Ba	0.007	0.008	0.010	0.003
I	1.613	1.310	1.727	1.923
X _{Mg}	31.421	32.457	48.097	29.278

that amphiboles are magnesio-hornblende and actinolites (Fig. 9).

The magnesium rich nature of the amphibole is reflected by its high Mg number (50% - 80 %). Si content ranges from (4.7 – 7.7 cation) but the majority of Si is less than 7.6. All the analyzed amphiboles contain sufficient Al to balance the Si deficiency in the tetrahedral sites.

The samples have low content of Na and K cations. The Na content in most of the samples ranges from 0.019 to 0.26 and K content ranges from .002 to 0.4. The studied samples have high Ca values, which reach 3.57 cation per

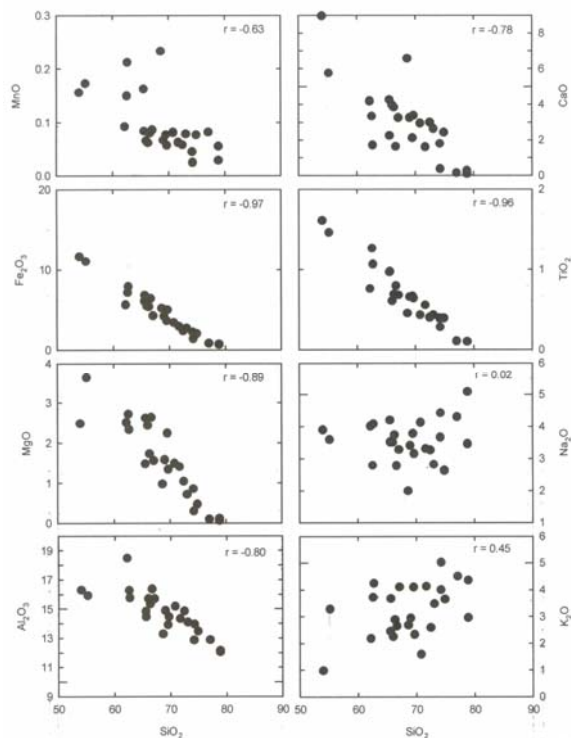


Figure 6. Plots of SiO₂ vs. major elements for metaconglomerates. Note the positive correlation for SiO₂-K₂O, the scatter between SiO₂-Na₂O and negative correlation for SiO₂ and other major elements.

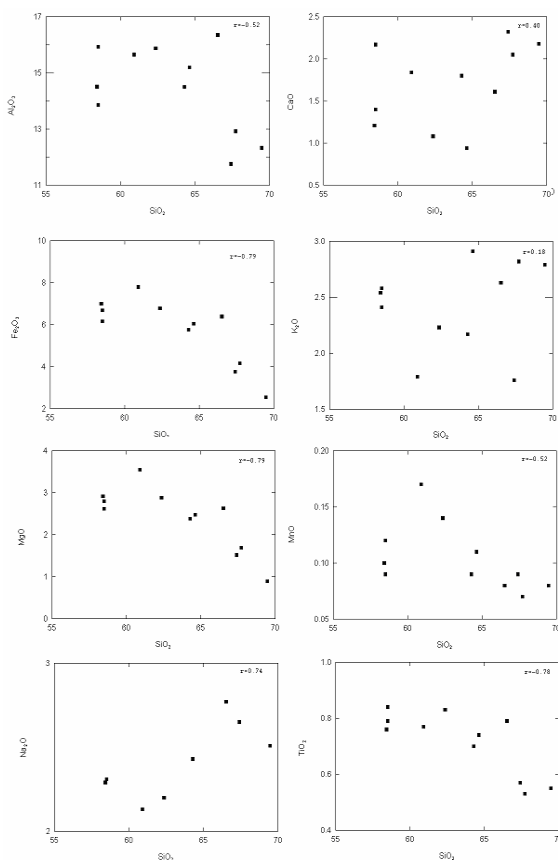


Figure 7. Plots of SiO₂ vs. major elements for hornfelses. Note the positive correlation for SiO₂ vs. K₂O, Na₂O and CaO and the negative correlation for SiO₂ and other major elements.

Table 5.a

Sample	54-X	54-X,	54-X	b-opaq	HC	b-	b-	HC
Na ₂ O	0.038	0.019	0.000	0.000	0.038	0.008	0.025	0.000
SiO ₂	0.017	0.033	0.000	0.026	0.013	0.020	0.024	0.031
MgO	0.019	0.003	0.003	0.000	0.020	0.000	0.024	0.001
Al ₂ O ₃	0.000	0.000	0.000	0.112	0.031	0.191	0.282	0.084
K ₂ O	0.023	0.039	0.000	0.000	0.020	0.000	0.008	0.013
CaO	0.030	0.066	0.155	0.064	0.198	0.079	0.079	0.248
FeO	46.261	39.112	35.215	91.957	79.626	92.083	90.894	84.095
TiO ₂	47.396	51.046	51.218	0.408	7.702	0.170	0.305	6.157
Cr ₂ O ₃	0.055	0.020	0.028	0.048	0.034	0.000	0.043	0.051
MnO	1.981	7.362	12.504	0.065	2.188	0.083	0.065	0.049
Sum	95.820	97.700	99.123	92.680	89.870	92.634	91.749	90.729
	Ilmenite	Ilmenite	Ilmenite	Magnetite	Titanomagnetite	Magnetite	Magnetite	Titanomagnetite

Table 5.b

Sample	H-II	H-II	H-II	Hc,	HC,
Na ₂ O	0.027	0.033	0.033	0.004	0.021
SiO ₂	3.566	3.244	3.280	31.129	30.206
MgO	0.309	0.398	0.320	0.000	0.000
Al ₂ O ₃	0.017	0.019	0.001	0.935	1.158
K ₂ O	0.000	0.025	0.000	0.000	0.002
CaO	0.304	0.296	0.196	28.118	26.682
FeO	75.592	75.232	73.095	1.349	1.888
TiO ₂	0.012	0.003	0.088	38.097	35.924
Cr ₂ O ₃	0.005	0.019	0.031	0.000	0.000
MnO	0.000	0.033	0.000	0.150	0.239
sum	79.832	79.302	77.044	99.782	96.120
	pyrite	Pyrite	pyrite	Titanite	Titanite

Table 5 (a,b). The chemical data for titanite, sulphide, and oxides.

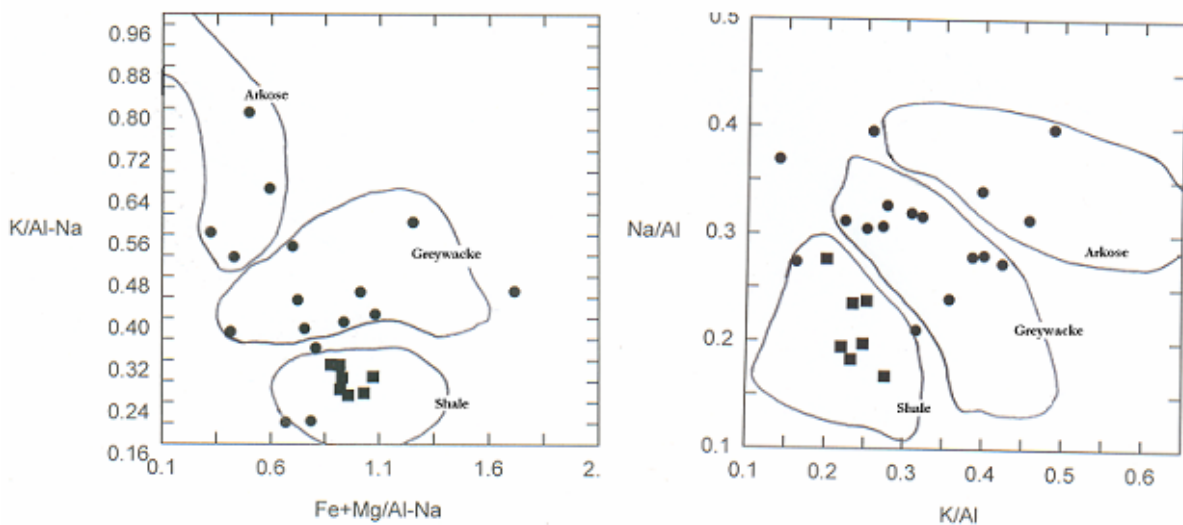


Figure 8. Plots of K/Al vs. Na/Al and (Fe+Mg)/(Al-Na) vs. K/(Al-Na) for the investigated rocks after (Saupé and Vegas, 1987). Note the hornfelses fall in shale field while the most of metaconglomerates fall in greywacke field and to lesser degree in arkoses field. The symbols as in (Fig. 6) and (Fig. 7).

unit formula. Table (6) shows the chemical formulas of selected amphiboles.

Table 6: The chemical analyses and formulae of amphibole.

Sample No.	A133	A1310	HC1	HC2
SiO ₂	48.43	51.32	53.16	53.86
TiO ₂	0.83	0.61	0.12	0.12
Al ₂ O ₃	6.16	4.86	2.2	1.49
Cr ₂ O ₃	0.04	0	0.01	0.02
FeO	15.29	13.53	8	6.46
MnO	0.43	0.53	1.33	1.15
MgO	12.56	14.2	14.34	14.52
CaO	11.98	12.14	20.6	23.84
Na ₂ O	0.74	0.46	0.43	0.41
K ₂ O	0.58	0.36	0.05	0.05
TOTAL	97.13	97.59	100.26	101.92
Si	7.186	7.435	7.444	7.393
Al ^{IV}	0.814	0.565	0.363	0.241
T site	8	8	7.807	7.634
Al ^{VI}	0.263	0.265	0	0
Cr	0.005	0	0.001	0.002
Fe ³⁺	0.026	0	0.595	0.741
Ti	0.093	0.067	0.013	0.012
Mg	2.778	3.066	2.993	0.134
Fe ²⁺	1.871	1.639	3.42	0
Mn	0.054	0.065	0.159	0.134
Ca	1.904	1.883	3.09	2.971
Na _B	0.006	0.015	0	0
Na _A	0.153	0.115	0.117	0.109
K	0.11	0.066	0.009	0.009

6. Geothermobarometry

Geothermometers are reactions that can be used to calculate or estimate temperature of formation of minerals (El shazly, 2001). The temperatures of equilibration applying the different calibrations (Powell & Powell (1977), Spencer & lindsley (1981), and Andersen & lindsley (1985)) for some samples using the ILMAT excel sheet by LePage is given in Table (7).

The amphibole chemistry, in particular their Al and Na contents, can be used to evaluate the P – T conditions of metamorphism (Laird and Albee, 1981). During low temperature metamorphism the amphiboles tend to have low Al content relative to high temperature igneous amphiboles (Leak, 1971).

The Na in the (B site) and Al^{IV} contents in metamorphic amphiboles tends to increase as the metamorphic grade increases (Laird and Albee, 1981). Spear (1980) has used the exchange equilibria between plagioclase and hornblende (NaSi ↔ CaAl) to estimate the temperature of

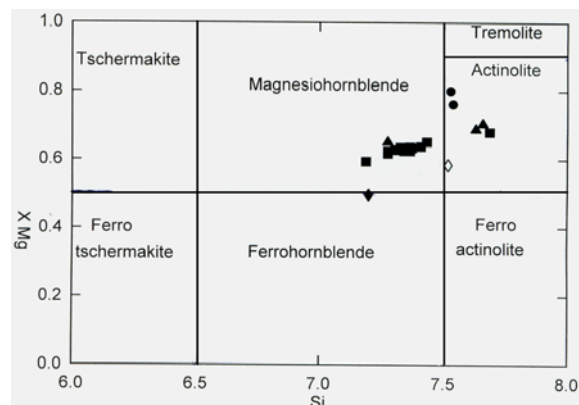


Figure 9. Mineral chemistry diagram of amphibole for the investigated rocks after (Leake, 1971). This figure is used to distinguish igneous from metamorphic amphiboles. Note that amphiboles fall exclusively in the metamorphic field. The symbols of samples are ■ represent A13 ▲ represent H11 ◇ represent 6-int.

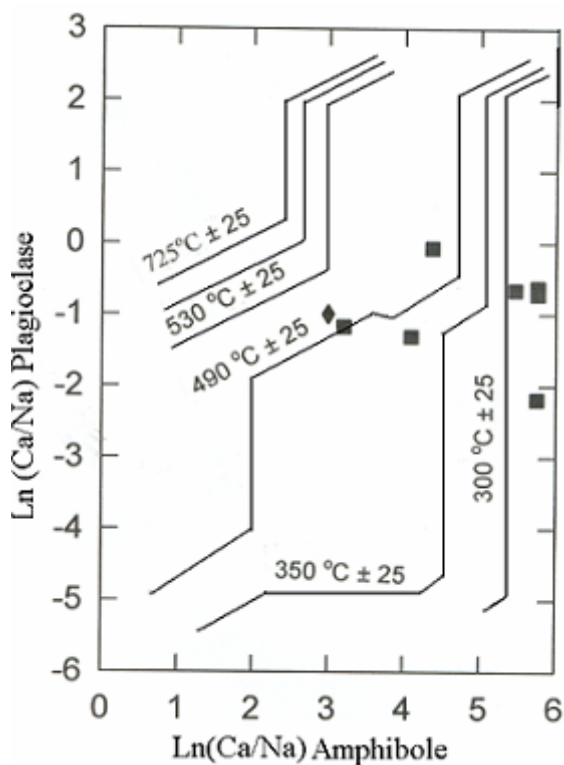


Figure10. $\ln(Ca/Na)_{Amph.} - \ln(Ca/Na)_{plag.}$ diagram for the investigated rocks after (Spear, 1981). The hornfelses were formed at about 500°C while the metaconglomerate were formed at temperatures between 490°C to less than 300°C. Symbols as in Fig. (9) ◆ represent X54.

amphibole formation during metamorphism. The $\ln(Ca/Na)_{plagioclase}$ vs. $\ln(Ca_{B\ site}/Na_{B\ site})_{amphibole}$ diagram developed by Spear (1980) is used to estimate the temperature of metamorphism.

The data points plot close to the isotherms 490 ± 20 to 530 ± 20 °C and 300 ± 20 °C thus indicating a temperature of formation between 300 – 500 °C (Fig 10).

Figure 12 adopted from Leake (1971) shows that most amphibole samples have relatively low temperature amphiboles relative to high temperature igneous

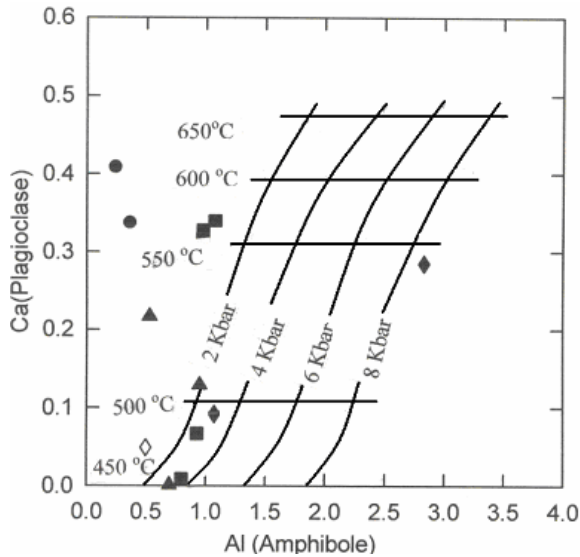


Figure 11. Al amphibole - Ca plagioclase diagram for the investigated rocks after (Plyusnina, 1982) is used to estimate the temperature and pressure of the metamorphic rocks. Note that metaconglomerates were formed at temperatures between 450°C to about 610°C and pressure less than 4Kbar, while the hornfelses were formed at 500°C and pressures of less than 4 Kbar. Symbols as in Fig. (9) and Fig. (10) ● represent Hc.

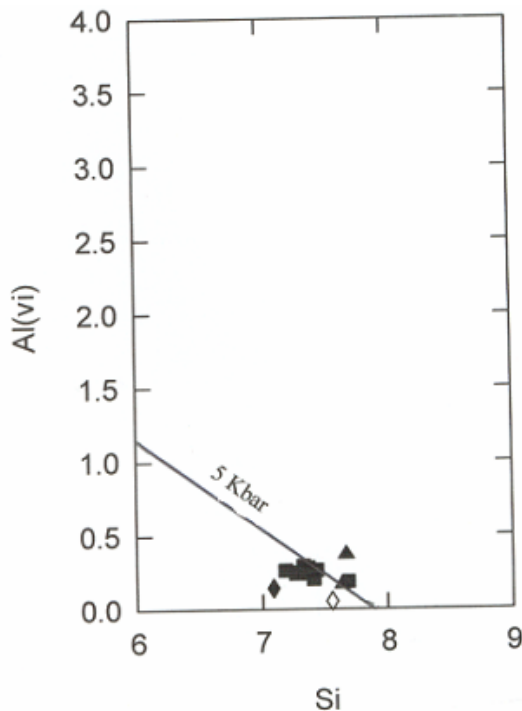


Figure 12. Al^{iv}- Si variation diagram for amphibole of the investigated rocks, after (Raase, 1974). Note that the majority of the amphiboles falls below the 5 Kbar curve. Symbols as in Fig. (9) and Fig. (10).

amphibole; this means these minerals were formed as a result of metamorphic processes.

Furthermore, Ca plagioclase vs. \sum Al amphibole diagram (Fig 11) after (Plyusnina, 1982) is used to determine the temperature and pressure of metamorphic rocks. This diagram shows that the temperature of

Table 7. Geothermometric results obtained by three magnetite – ilmenite calibrations.

Sample no.	Average temp °C after Powell & Powell (1977)	Average temp °C after Spencer & lindsley (1981)	Average temp °C after Andersen & lindsley (1985)
b1	560	651	658
b2	333	468	463
HIII	370	492	490
HII2	308	437	428
HC	510	535	545

equilibration does not exceed 570 °C and the ranges between 450 to 610 °C, while the pressure does not exceed 4 Kbar with the exception of X54.

Amphiboles plot on the Al^{iv} vs. Si variation diagram (Raase, 1974) to the left of the 5- Kbar boundary or close to it (Fig 12).

7. Discussion and Conclusions

7.1. Economic Minerals (Sulfide Minerals)

Opaques are abundant in the metasediments and the intruded igneous dykes.

X- ray diffraction study has indicated that 12 out of 25 analyzed samples contain sulfide minerals (Fig 13). Pyrite, cinnabar, pyrrothite, sphalerite, galena and chalcopyrite ferromagnesian silicates such as, biotite, amphibole, cordierite and chlorite in addition to garnet, staurolite are common constituents of silicate rocks that

host metamorphosed sulfides. These minerals become more magnesium with rich proximity to sulfide ore as a result of the effects of metamorphism and the increased f_{O_2} and f_{S_2} (Rosenberg, et al. 2000).

are distinguished as sulfides in the study area. However, the most widespread sulfides in the analyzed samples are chalcopyrite and pyrite.

Rosenberg, et al. (2000) has noticed that the samples with (>1 %) total sulfur shows a marked divergence between the iron content of the ferromagnesian mineral and the whole rock composition. This divergence reflects the sequestering of iron into sulfides, so that the ferromagnesian silicates have low X_{Fe} even though the rocks as a whole may be iron rich. This result agrees with the result of the analysis of biotite, pyroxene, and amphibole in the samples (A9, X51, X54, HC).

For example:

i) The X_{Fe} of biotite and pyroxene in A9 sample equals 51.9 and 44.6 respectively, while of the X_{Fe} of the whole rocks A9 equals to 84.1.

ii) X_{Fe} of biotite, pyroxene and amphibole of HC sample is 68.7, 28.2 and 36.2, respectively and X_{Fe} of the whole rock equals 73.38.

iii) X_{Fe} value of X51 sample equals 73.3 while the X_{Fe} of the whole rock equals 95.1.

The decrease of X_{Fe} of the ferromagnesian mineral especially of the biotite relative the whole rock results

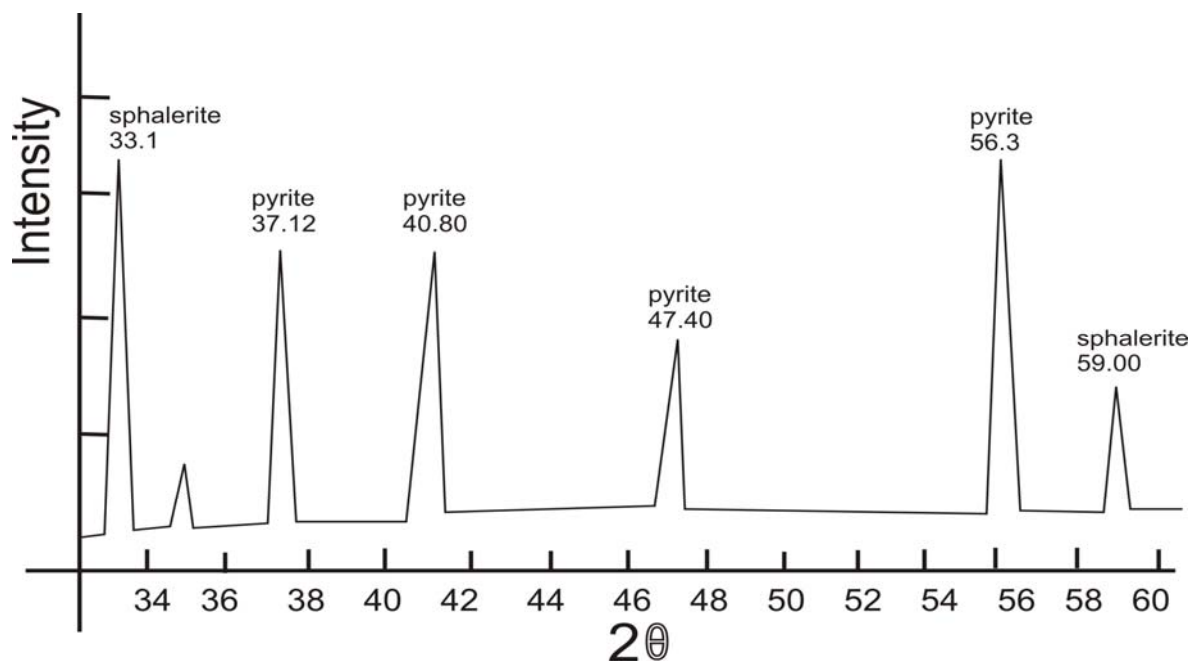


Figure 13. XRD pattern of metaconglomerates sample contain some of sulphide minerals.

from the increase of fO_2 . The increase of oxygen fugacity is elevated; the iron in this mineral is oxidized into ferric state.

The Fe^{+3} cannot enter most $Fe^{+2} - Mg$ silicate of metamorphic rocks such as biotite and cordierite, (Hyndman, 1985), therefore the X_{Fe} of ferromagnesian minerals becomes lower than X_{Fe} of the whole rocks.

Sample X51 has Fe_2O_3 (Fe^{+3}) of 38.3 and FeO (Fe^{+2}) of 22.4. The high value of Fe^{+3} reflects the high fO_2 and the enrichment with sulfide minerals. This result agrees with the hand specimen inspection and the mineral chemistry.

Larsen et al. (1995) have noticed that the biotite in rocks in and immediately adjacent to sulfide ore are enriched in fluorine; and biotite rich in fluorine tends to have low iron content due to $Fe - F$ avoidance (Rosenberg et al., 2000)

A9, X51 and HC samples have relatively high fluorine values of 0.94, 0.25 and 0.095% respectively.

On the basis of the above observations, it is suggested that the opaque minerals in the study area are discouraging to consider them of economic value.

7.2. Geothermobarometry

7.2.1. Hornfelses

The plagioclase in the hornfelses has an oligoclase and andesine composition. It becomes more calcic and changes from albite in greenschist facies to oligoclase in epidote amphibolite facies (Barker, 1990). The low temperature limit of amphibolite facies is set by appearance of oligoclase (Hyndman, 1985).

Some samples contain sillimanite and do not contain cordierite. Sillimanite in these samples could be the result of the reaction:

Garnet + cordierite = biotite + sillimanite (Katz et al. 1998).

The mineral content and the temperature and pressure of formation of the analyzed samples confirm their

occurrence in the amphibolite facies close to the contact with the intruded granite.

7.2.2. Metaconglomerate

The amphiboles in metaconglomerates samples are actinolite, actinolitic hornblende and magnesian hornblende. Actinolite is a characteristic mineral of the greenschist facies (Klein, 2002). Prograde metamorphism changes amphibole composition from actinolite to hornblende (Laird and Albee, 1981). Plagioclase also becomes more calcic with increasing the metamorphic grade and the presence of oligoclase characterizes the epidote amphibolite facies. (Barker, 1990)

Plagioclases in A13 and HC are of andesine composition, and in other samples as indicated by the X-ray diffraction results into oligoclase, albite and labradorite.

The different types of plagioclase minerals in the same samples reflect the different origin of rocks. Diopside also exists in sample HC and was identified by microscope and X-ray in some other samples. Barker (1990) suggested that the coexistence of tremolite and diopside is characteristic of temperatures of the order 500–650 °C. Depending on the pressure and temperature of formation, texture, mineralogical composition, and chemical data, metamorphism belongs to a greenschist to amphibolite facies

8. Acknowledgements

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Compressive Strength of Vuggy Oolitic Limestones as a Function of Their Porosity and Sound PROPAGATION

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Abstract

Vuggy oolitic limestones have been screened previously based on the determination of their cementation exponent (m) values. The higher the m values above 2, the higher the percentage of separated vugs. Uniaxial compressive strength of 15 French vuggy limestones has been characterized using the velocity of sound and some pore-related properties. The work resulted in 10 equations that predict compressive strength from velocity of sound, saturation coefficient, cementation exponent (m), permeability, and porosity (total, sonic, secondary, matrix, and vug). Practical implications of the present work and its limitations have also been discussed.

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Keywords: Uniaxial Compressive Strength; Velocity of Sound; Secondary Porosity; Vug Porosity; Limestone; Oolitic; Petrophysics; Jurassic; France.

1. Introduction

The Many technical and industrial aspects of carbonates are related directly or indirectly to their pore microstructure, which is complicated in comparison to that in the siliclastics (Mazzullo and Chillingarian, 1992). Hence, the amount and type of secondary porosity (relative to total porosity) and its distribution within the rock exert strong control on the usefulness of a carbonate rock as an oil reservoir. Applications include production and stimulation characteristics of carbonate reservoirs (Jordy, 1992; Chillingarian et al., 1992; Hendrickson et al., 1992; Honarpour et al., 1992; Wardlaw, 1996), salt durability (Leary, 1983) and restoration of stone (Ashurst and Dimes, 1990; Spry, 1982).

According to Choquette and Pray (1970), limestone's porosity is either (1) primary with pores occurring between particles or crystals or within them, or formed by gas bubbles and sediment shrinkage (*fenestral porosity*), and as *shelter* or *growth-framework pores* (common in reef buildups); or (2) secondary porosity (Mazzullo, 2004): which is formed by post-depositional dissolution (by freshwater and/or aggressive fluids), or fracturing. Thus, most of the porosity in limestone reservoirs is of secondary origin. Cavernous and associated vuggy porosity present in oolitic limestones are dominant in some building stones (Honeyborne, 1982; Leary, 1983) and constitute major attributes of hydrocarbon production (Newell et al. 1987; Mazzullo and Chillingarian, 1996; Yousef and Norman, 1997; Fox & Albrandt, 2002).

Where sophisticated laboratory tests are rarely performed due to high expenses or lack of facilities, there is a need to develop simple estimation schemes by which different porosity types and quantities are defined. This will be of importance for interpretation of geophysical logs at the well site (with none or minimum amount of laboratory work). The present author (Moh'd, 2007) characterized the secondary porosity of some Jordanian building limestones using easily measured properties (total porosity, water saturation and velocity of sound V_p).

Unconfined Compressive Strength (UCS), the most frequently used strength test for rocks is their ability to withstand crushing under direct pressure, as in blocks and columns (Fox, 1923) or '*the stress required to break a loaded sample that is unconfined at its sides*'. (Krynine and Judd, 1957). Carrying out the test usually follows ASTM designation C-170: Compressive strength of building stones and preparation of the test specimens is time consuming. Compressive strength can be defined as the load per unit area at which a block fails by shear or splitting. Test specimens are in the form of cubes or cylinders (with preferably 2:1 length to diameter ratio). The test is usually carried out on dry or saturated samples perpendicular to or parallel to bedding.

Test results are affected by internal and external factors. The former includes mineralogy (especially quartz content, cement type, clay minerals) and fabric; the way in which the crystals are assembled (Price 1960; Lamar 1967; Vutukuri et al. 1974; Dearman 1974 and 1976; Irfan and Dearman 1978; Mogilevskaya 1965), size and shape of grains (Brace 1961; Skinner 1959; Lamar 1967), density and porosity (Attewell and Farmer 1976; Smoradinov et al. 1970; Hoshino 1974), water content (Ruiz 1966; Feda 1966; Korkosky and Husale 1968; Duncan 1969; Parate 1973; Mogilevskaya 1970; Broch 1974, 1979; Boozer et al. 1963; Pugh 1967), temperature (Hawkes and Mellor

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1970; Mellor and Rainey 1968, 1969; Brighenti 1970), and anisotropy (Somerton et al. 1970; Al-Jassar and Hawkins 1979; Stoney and Dhir 1977; Jovanic 1970). External factors are related to the test conditions and include both specimen geometry and testing state. These factors include specimen geometry (aspect ratio (height/diameter, h/d) and size) Hawkes and Mellor, 1970; Vutukuri et al., 1974; Obert and Duvall (1967); Bieniawski 1973; Vutukuri et al. 1974; Hosking and Horino 1986; Hudson and Cook 1970; ISRM 1979), core ends and rate of coring in addition to capping material and loading rate (Obert et al. 1964; Perkins and Green 1970; Houpert 1970).

In a previous paper (Moh'd, 2008), the amount of vug porosity has been estimated in many oolitic limestones including 15 samples representing 8 French building limestones. The present work aims at investigating how the uniaxial compressive strength of these limestones is related to velocity of sound, saturation coefficient and modified saturation, cementation exponent (m), permeability, and the different types of porosity (total, sonic, secondary, matrix, vug).

2. Materials and Methods

The studied stones along with their salient petrographic features have been summarized in Table 1 after Honeyborne (1982). As can be seen in this table, most of the studied stones are oolitic limestones of dominantly Jurassic age. Eight stones with 16 subtypes have been covered in this study.

Table 1. Notes on the studied limestone (modified after Honeyborne, 1982).

Stone name	Description	Sparite / micrite	Sample No.
Savonnieres	Shelly oolitic limestone, average oolite diameter 0.5 mm	sparite	6, 7, 8
Brauvilliers	Oolitic limestone with occasional shell fragments	sparite	9, 10, 11
Anstrude	Bathonian, crinoidal oolitic limestone	micrite	14, 15, 16
Massangis	Oolitic limestone with shell fragments and occasional nodules of silica and/or pyrite	micrite	20
Vilhonneur	Oolitic limestone, oolites fine-medium	sparite	37, 38, 39
Sireuil	Cenomanian, fine-medium, oolitic limestone with quartz microfossils	micrite	40
Terce	Callovian, chalky oolitic limestone, very fine, dominantly microporous with occasional macropores.	micrite	50
Chauvigny	Bathonian, oolitic limestone	sparite	53

The results of compressive strength (on 70 mm cubes), porosity, degree of saturation, and sound velocity (V_p) tests, which were carried out following the French procedures (Mammilan, 1976), were taken from Honeyborne (1982).

Derived properties include:

Modified saturation: this was obtained by multiplying total porosity with degree of saturation.

Cementation exponent m : this parameter, which is positively related to the separated vugs as suggested by Lucia (1983), was calculated using Archie formula and

assuming that water resistivity as 0.005 (Archie, 1952) where $m = \log(0.005/\text{water saturation squared})/\log \text{ total porosity}$. This parameter can also be estimated from total and sonic porosity for fractured (Rasmus, 1983) and vuggy carbonates (Nugent, 1983).

Permeability: was obtained using Jorgensen equation (1988) by multiplying 84105 by porosity index = $\Phi^{m+2}/(1-\Phi)^2$. This number (84105) is the proportionality constant in permeability-porosity index equation. The obtained values were found to correlate well with measured air permeability using API standards.

Sonic porosity: is equivalent to velocity of sound – $141/(28.59)$; where 28.59 is the inverse of $100/(3000-141)$; 141 and 3000 are transit time (in μ s/m) in calcite crystal and air, respectively.

Vug porosity and *Fracture porosity*: are estimated from the dual porosity chart of Aguilera and Aguilera (2003).

Matrix porosity is the total porosity minus the sum of vug and fracture porosities.

In summary the cementation exponent m has been estimated for each stone type. Then those stones with m more than 2 have been considered of vug porosity. After that, only oolitic limestones with m more than 2 have been dealt with. Oolitic limestones have been identified after consulting the description of each stone in Honeyborne (1982).

3. Results

Properties of vuggy French oolitic limestones taken from Honeyborne (1982) are listed in Table 2, and those derived by the author using the methods applied in the previous section are in Table 3. The different properties are correlated in Table 4. A statistical summary is shown in Tables 5 and 6. Bivariate plots between unconfined compressive strength and other properties are shown in Figures 1 to 10. The results of the work are summarized in Table 7. The relationship between UCS and each variable has been examined by fitting linear, logarithmic, power or exponential equations of the Excel program. The selected relationship shown in Table 7 is the one having the best fit (maximum correlation coefficient r), on one hand, and avoiding negative values of UCS or other variables, on the other (when the curve extended). Equations in Table 7 are arranged (in descending order) based on correlation coefficient r -values.

The studied oolitic limestones range in their compressive strength from 10.4 to 80.2 MPa, thus classified according to Deere and Miller (1966) into very low strength (< 28 MPa, samples 6, 7, 8, 9, 10, and 40), low strength (29-56 MPa, samples 14, 15, 50, 53) and medium strength (56-112, samples 20, 38, 39).

Figure 1 shows that there is an almost perfect ($r = 0.983$) positive relationship (power function) between compressive strength and dry density. The very strong ($r = 0.91$) positive exponential relationship between velocity of sound and compressive strength (Figure 2) reveals that the latter can be estimated by the non-destructive sonic velocity test. There seems to be a critical value of velocity at about 4000 m/s above which compressive strength increases rapidly.

A very strong ($r = -0.98$) negative exponential relationship (Figure 3) occurs between total porosity and

compressive strength. Below a critical porosity value of about 25%, compressive strength changes quickly. Figure 4 shows an inverse logarithmic relationship ($r = -0.77$) between modified saturation and compressive strength. Below a modified saturation value of 15 compressive strength changes rapidly.

Figure 5 shows an inverse relation ($r = -0.89$) between cementation exponent m value and compressive strength. The higher the percentage of separated vugs (expressed by higher values of cementation exponent m), the lower the compressive strength is. Compressive strength changes rapidly below a cementation exponent value of 3.

Figure 6 shows an inverse relation ($r = -0.95$) between permeability and compressive strength. The latter drops quickly when the value of permeability reaches 50-60 md, then the rate of strength decrease becomes lower as the permeability increases.

Figure 7 shows an inverse relation ($r = -0.91$) between uniaxial compressive strength and sonic porosity. Compressive strength changes quickly below a sonic porosity value of about 5%.

Figure 8 shows an inverse relation ($r = -0.96$) between uniaxial compressive strength and secondary porosity. Compressive strength changes rapidly up to a secondary porosity value of about 16%.

Figure 9 shows an inverse relation ($r = -0.92$) between uniaxial compressive strength and vuggy porosity. Compressive strength changes rapidly below a vuggy porosity value of about 10%.

Figure 10 shows an inverse linear relation ($r = -0.82$) between uniaxial compressive strength and matrix porosity.

Table 2. Properties of vuggy French oolitic limestones taken from Honeyborne (1982).

Sample No.	Density (g/cm ³)	Compressive Strength (MPa)	Sound Velocity (m/s)	Porosity (%)	Saturation Coefficient (%)
6	1.721	11.2	2881	36.1	0.52
7	1.748	11.2	2684	34.7	0.5
8	1.82	17	2702	30.6	0.68
9	1.959	23.2	3106	27	0.57
10	1.826	17.6	2966	32.6	0.54
11	1.766	11.9	3045	33.7	0.47
14	2.114	45.6	3376	21.9	0.81
15	2.14	41.1	3374	20.6	0.66
16	2.218	58.1	4282	18.1	0.65
20	2.3	80.2	4276	15.1	0.88
38	2.392	65	4259	11.7	0.94
39	2.389	76	4606	11.9	0.64
40	1.727	10.4	2069	36	0.76
50	2.061	36.2	3332	23.7	0.88
53	2.201	38.3	4014	18.7	0.71

Table 3. Derived properties of vuggy oolitic limestones.

Sample No.	Modified Saturation	Cementation Exponent m	Permeability millidarcies	Sonic Porosity%	Secondary Porosity %	Vug Porosity %	Matrix Porosity %
6	18.77	3.92	494.61	7.2	28.9	22.5	13.6
7	17.35	3.7	473.01	8.1	26.6	22	12.7
8	20.81	3.82	177.42	8.0	22.6	18	12.6
9	15.39	3.19	176.58	6.3	20.7	17	10
10	17.6	3.63	336.45	6.9	25.7	19	13.6
11	15.84	3.48	493.41	6.6	27.2	20	13.7
14	17.74	3.21	30.8	5.4	16.5	13	8.9
15	13.6	2.83	64.74	5.4	15.2	10	10.6
16	11.77	2.6	48.26	3.2	14.9	8.5	9.6
20	13.29	2.67	17.09	3.3	11.9	10	5.1
38	11	2.41	8.39	3.3	8.4	4.1	7.6
39	7.62	2.07	18.72	2.7	9.3	1.25	10.7
40	27.36	4.65	230.08	12.0	24.0	22.5	13.5
50	20.86	3.5	52.59	5.6	18.1	14	9.7
53	13.28	2.75	44.25	3.8	14.9	5.3	13.4

Table 4. A correlation matrix between the different properties.

	Density	Comp. strength	Sound velocity	Porosity	Saturation Coef.	Mod. saturation	m	Permeability	Sonic porosity	Secondary porosity	Vug porosity	Matrix porosity
Density	1.00											
Compressive strength	0.96	1.00										
Sound velocity	0.93	0.92	1.00									
Porosity	-1.00	-0.95	-0.93	1.00								
Saturation coefficient	0.62	0.61	0.39	-0.62	1.00							
Modified saturation	-0.77	-0.73	-0.88	0.77	-0.01	1.00						
m	-0.92	-0.87	-0.96	0.92	-0.28	0.95	1.00					
Permeability	-0.86	-0.80	-0.67	0.87	-0.78	0.40	0.65	1.00				
Sonic porosity	-0.88	-0.84	-0.97	0.88	-0.31	0.90	0.96	0.61	1.00			
Secondary porosity	-0.98	-0.94	-0.86	0.98	-0.69	0.68	0.85	0.91	0.79	1.00		
Vug porosity	-0.97	-0.88	-0.92	0.97	-0.51	0.80	0.92	0.82	0.87	0.95	1.00	
Matrix porosity	-0.74	-0.82	-0.63	0.74	-0.71	0.44	0.60	0.70	0.62	0.75	0.56	1.00

Table 5. Statistical summary of properties tested by Honeyborne (1982).

	Density	Comp. strength	Sound velocity	Porosity	Saturation coefficient
Mean	2.03	36.20	3398.13	24.83	0.68
Standard Error	0.06	6.30	189.76	2.26	0.04
Standard Deviation	0.25	24.40	734.95	8.75	0.15
Range	0.67	69.80	2537	24.40	0.47
Minimum	1.72	10.40	2069	11.70	0.47
Maximum	2.39	80.20	4606	36.10	0.94
Count	15	15	15	15	15

Table 6. Statistical summary of derived properties.

	Modified Saturation	m	Permeability	Sonic porosity	Secondary porosity	Vug porosity	Matrix porosity
Mean	16.15	3.23	177.76	5.84	18.98	13.81	11.02
Standard Error	1.24	0.18	47.79	0.64	1.72	1.82	0.67
Standard Deviation	4.81	0.68	185.08	2.48	6.67	7.04	2.59
Range	19.74	2.58	486.22	9.31	20.47	21.25	8.6
Minimum	7.62	2.07	8.39	2.66	8.42	1.25	5.1
Maximum	27.36	4.65	494.61	11.97	28.89	22.5	13.7
Count	15	15	15	15	15	15	15

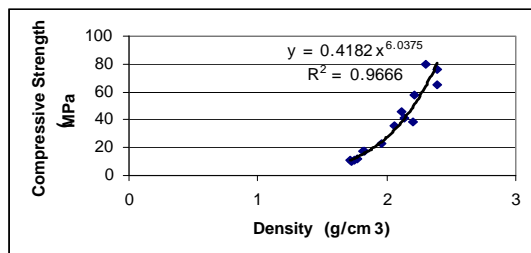


Figure 1. Density versus compressive strength.

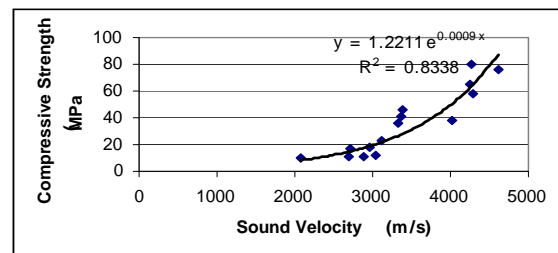


Figure 2. Sound velocity versus compressive strength.

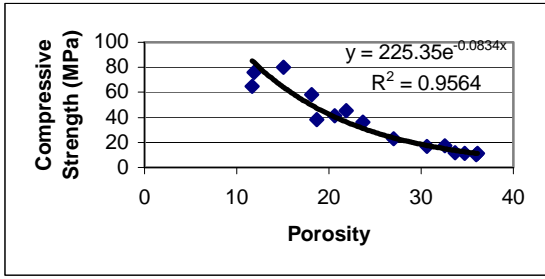


Figure 3. Total porosity versus compressive strength.

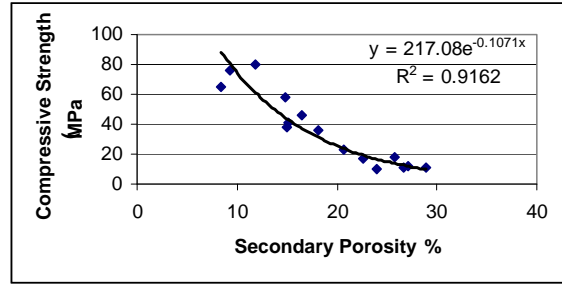


Figure 8. Secondary porosity versus compressive strength.

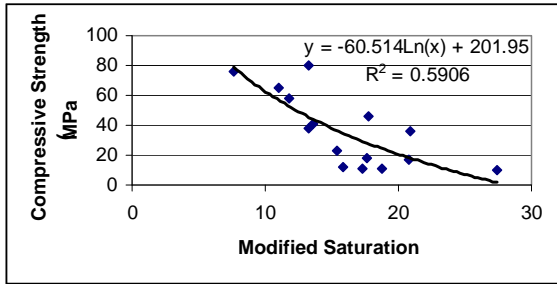


Figure 4. Modified saturation versus compressive strength.

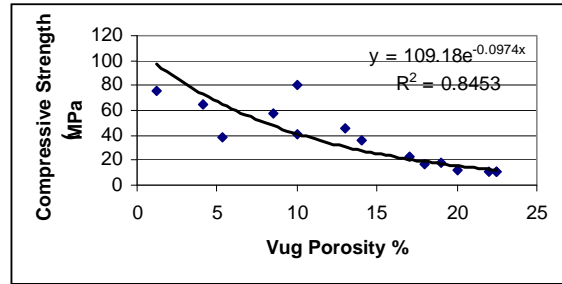


Figure 9. Vug porosity versus compressive strength.

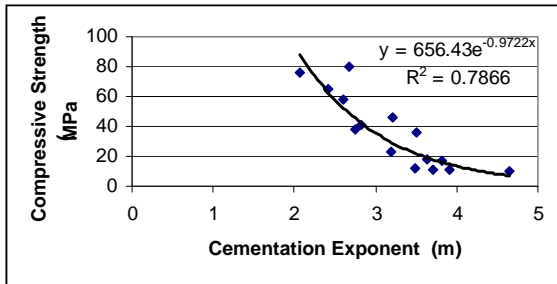


Figure 5. Cementation exponent versus compressive strength.

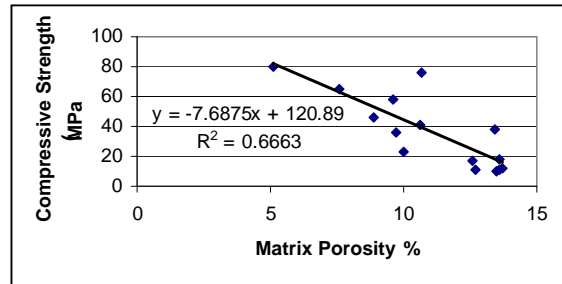


Figure 10. Matrix porosity versus compressive strength.

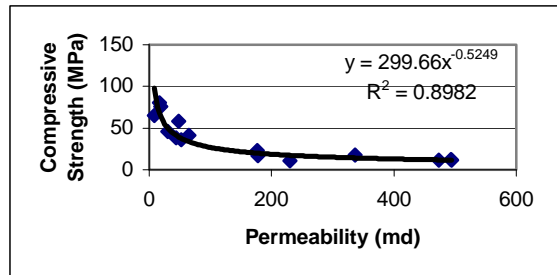


Figure 6. Permeability versus compressive strength.

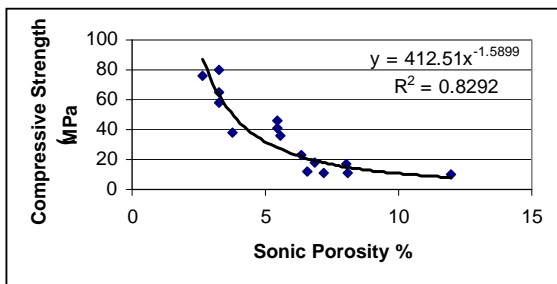


Figure 7. Sonic porosity versus compressive strength.

Table 7. A list of significant relationships between compressive strength and other parameters illustrated in Figures 1 to 10.

Fig.	Equation	R ²	R
1	UCS = 0.4182 density ^(6.0375)	0.9666	+0.9832
2	UCS = 225.35/e ^(0.0834 porosity)	0.9546	-0.9777
3	UCS = 217.08/e ^{1.071 (secondary porosity)}	0.9162	-0.9572
4	UCS = 299.66/permeability ^{0.5249}	0.8982	-0.9477
5	UCS = 109.18/e ^{0.0974 vuggy porosity}	0.8453	-0.9194
6	UCS = 1.2211 e ^{0.0009 (sound velocity)}	0.8338	+0.9131
7	UCS = 215.51/sonic porosity ^(1.5899)	0.8292	-0.9106
8	UCS = 656.43/e ^{0.9722 (cementation exponent)}	0.7866	-0.8869
9	UCS = -7.6875 (matrix porosity) - 120.89	0.6663	-0.8163
10	UCS = -60.514 Ln (modified saturation) + 201.95	0.5906	-0.7685

4. Discussion of Results

In almost all the previous cases the best-fit curve shown represents approximately the average value of compressive strength. Lower and upper envelopes can be made by connecting the lowest points below the curve (lower envelope) and the highest points above the best fit-curve (upper envelope). As it is well known that micrite imparts higher strength to the rock than sparite, it is believed that the upper envelope is related to the highest micrite contents, whereas the lower envelope is related to highest sparite contents. The upper and lower envelopes may also be related to other factors such as mineralogical constituents other than carbonates (e.g. silicification), and vug-size distribution. These points were not tackled in the present work, but indicated the importance of integrating petrographic investigations with any geotechnical study on vuggy oolitic limestone.

The strong relationship between compressive strength and both total porosity and velocity of sound reflects, more or less, homogenous nature of the studied samples. This idea is further supported by plotting the total porosity (on the x-axis) and the sonic velocity (on the y-axis) (Figure 11). In this case the samples will be aggregated and nicely fitted by one straight line (see also Moh'd, 2008). Had the studied suite of samples been of heterogeneous nature, it would have been plotted in the total porosity- sonic velocity graph, as seen in Figure 12 which shows a weak inverse relation and high scattering of data. Figure 12, which includes 47 UK oolitic limestones, was drawn after screening Leary (1982) data. If fitted with one curve, then R^2 is much lower than that shown in Figure 11. This indicates the high complexity of the pore structure of the UK oolitic limestones in comparison to that of the French stones. Unfortunately, compressive strength of these stones was not provided by Leary (1983).

If the vugs presence is ignored, then an idea about the uni- or bimodality of pore space can be gained from the degree of saturation values. The studied suite of rocks has a degree of water saturation ranging from 0.47-0.94. Limestones, having their pore space in the form of finer capillaries, will have high values of water saturation (samples 38, 50, 20). This usually occurs in the micro pores of the vuggy oolitic limestone. When the degree of saturation is less than 0.60, then the pore space is bimodal (have 2 capillaries r and R , samples 6, 7, 9, 10, and 11). The remaining samples are either of unimodal or slightly bimodal pore space (small difference between r and R). This can be further checked by plotting porosity against modified saturation (Bellanger et. al., 1993; Moh'd, 2008). As seen in Figure 4, the compressive strength has a negative relation with modified saturation. Being equivalent to porosity multiplied by saturation, modified saturation can be thought of as equivalent to the amount of water that the limestone can accommodate in its interconnected pore space. This property is referred to as 'bulk volume water' in petrophysics literature.

The higher the cementation exponent m value above 2, the higher the proportion of isolated vugs is, and

consequently the lower the compressive strength. Vuggy porosity has a relationship with compressive strength similar to that of cementation exponent since cementation exponent is used in deriving vuggy porosity using Aguilera and Aguilera (2003) method.

5. Practical Implications, Limitations and Suggestions

To estimate the uniaxial compressive strength in the case of vuggy oolitic limestone, and when it is difficult to have access to sophisticated equipment, the easiest parameter to measure is dry density, which can be inverted to compressive strength using Figure 1. As a double check, total porosity can be measured (or derived from dry density) to estimate compressive strength using Figure 2.

The number of samples included in the present database is relatively small. Being collected from one region (France), thus possibly reflecting one sedimentary basin may be the reason for the homogenous nature of the studied samples. Consequently, extending the present study to include analyses of larger databases collected from different sedimentary basins may be necessary to show potential heterogeneities.

The suite of rocks studied in this work is predominantly of very low-to-low compressive strength. Results from this work should not be generalized to strong or very strong rocks without further testing. It is believed that the compressive strength of the latter types of rocks will be more affected by the presence of vugs especially if they have a micritic matrix and/or low porosity (e.g. Carboniferous limestones of England). As pointed out in the discussion section, the reason of the scattering of the data points in the different figures may be better understood if the physical and engineering properties are integrated with a petrographic study. Here factors such as micrite and sparite contents, non-calcareous minerals (silicification for instance), type of cements and the nature of their distribution, oolites size and distribution, and fracture-vug relationships and vug size distribution should be emphasized.

6. Conclusions and Recommendations

Compressive strength of the studied samples has positive relationships with density and sonic velocity and inverse relationships with permeability, modified saturation, total and other porosity types. This parameter can be derived from dry density alone. It can also be estimated from the knowledge of porosity types and amounts with accuracy decreasing in the following order: total porosity, secondary porosity, vuggy porosity, sonic porosity and matrix porosity. From a practical point of view, dry density, which is the easiest parameter to measure, can be used for predicting compressive strength. Carrying out a study including vuggy oolitic limestones spanning the whole range of strength (very low to extremely strong), and integrated with petrographic investigations is highly recommended.

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Quality Assessment of Harvested Rainwater for Domestic Uses

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Abstract

Despite continuous monitoring of public water supplies by governmental agencies, little is done for monitoring the water quality of cisterns and tanks receiving rainwater. For this reason, it is very important to evaluate the quality of rainwater collected and stored in these cisterns and storage tanks. In the present work, a comprehensive survey was carried out to cover four governorates in northern region of Jordan, where rainwater collection for domestic use is practiced on regular basis. Ninety samples of harvested rain water from various storage tanks within these four governorates were collected and analyzed for different quality parameters (pH, alkalinity, Hardness, Turbidity, TDS, COD, NO₃, NH₄, PO₄, Pb, Fe, Cr and biological contaminations). The results of the analysis were compared with valid quality guidelines to evaluate its suitability for domestic uses. The resulted data indicate that water quality in these tanks and cisterns varies depending on location, on catchment area, and on the availability of public sanitary systems. It was concluded that collected rainwater is unsuitable for drinking purpose while it could be used for irrigation within in houses.

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Keywords: Water Harvesting; Water Quality; Cisterns; Drinking Water, Jordan .

1. Introduction

The high population growth rate in Jordan together with the rapid economic developments have been accompanied by an increase in water demand, while the available water resources are limited and decreasing. Jordan's water resources are, on per capita basis, among the lowest in the world. The available water from existing renewable sources is projected to fall from 160 m³/capita/year in 2008 to 91 m³/capita/year by the year 2025, which is very low in comparison with the international water poverty line of 1000 m³/yr (Alzboon, *et al.*, 2008, Bataineh, *et al.*, 2002). Water shortage has forced Jordan to prospect for new non-traditional water resources to narrow the gap between demand and availability.. Water harvesting is considered as an attractive option for this purpose.

Rainwater harvesting is still the only source of potable water for rural communities where there are no water supply networks (MWI, 2009). Even in some areas where potable water is supplied by networks, harvested rainwater is still a significant supplemental resource for domestic uses, especially during summer season when low quantity of water is supplied. Currently in Jordan, roof top rainwater harvesting is being practiced for drinking water, domestic uses, and livestock and for garden irrigation. (MWI, 2009). Due to the importance of collected rainwater especially in the arid areas, rain water harvesting and its

quality are the focal points of several ongoing researches. For example, a research study in China investigated the effect of the types of roof on rainwater quality. The study indicated that the measured inorganic compounds in the rainwater harvested from roof-yard catchments systems generally matched the WHO standards for drinking water, while the concentrations of some inorganic compounds of the rainwater collected from land and road surfaces appeared to be higher than the guideline values for drinking water (Zhu, *et al.*, 2004). A similar study by Yaziz, *et al.*, (1989) concluded that there were significant variations in the concentrations of pollutants of water samples collected from tiles roofs and galvanized iron roofs. Additionally, it was found that the concentration of various pollutants were higher in the first spill of rain in comparison with the next spills. Jiries, *et al.*, (2002) determined the metallic content and inorganic constituents of street sediments and street runoffs in Amman/Jordan. The highest concentrations of all constituents were detected during low rainfall and long dry periods of atmospheric deposition preceding rainfall events. However, high levels of both lead and copper were recorded which might be attributed to traffic pollution. An investigation of rainwater quality found that there is a correlation between water quality and intensity of rain. Values of pollutants (COD, BOD, N, and P) were found to be higher in case of moderate rain, while in samples taken during a heavy rainstorm; the components were less concentrated, as the rain washed the contaminants (Teemusk, *et al.*, 2007). In 1985, a study was conducted in Portuguese west coast to determine seasonal variations of rainwater. It was found that the minimum concentrations of phosphate and nitrates were registered during autumn

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while the maximum were recorded during winter and spring (Pio, *et al.*, 1985). Other studies showed that the location of sampling points, weather conditions, and industrial, urban or agricultural activities have significant effects on chemical composition of collected rainwater (Vazquez, *et al.*, 2003, Abbas, *et al.*, 1993, Meera, *et al.*, 2006). Zunckel *et al.* (2003), found that there is a strong correlation between the present of contaminants in the catchments area and rainwater quality. A correlation between nitrate and ammonium is attributed mainly to livestock and fertilizer use. Correlations between fluoride and organic acids suggest a contribution from activities such as biomass burning, the use of fuel wood, agro industries and the use of crop fertilizer. Concerning the physico-chemical and microbiological determinants, a study which was conducted in New Zealand demonstrated that roof-collected rainwater systems provide potable supplies of relatively poor physicochemical and microbiological quality (Greg, *et al.*, 2001).

The majority of local & international research studies in this area have focused on the assessment of rain water quality, which is immediately collected after rainfall events. Because there is a possible change in water quality during long periods of storage, this study investigates the quality of harvested rain water after its collection and storage in tanks.

In Jordan, governmental agencies continuously monitor public water supplies, but little attention has been done for monitoring water quality of cisterns and tanks receiving rainwater. This study was conducted to identify and quantify sources of contaminations in harvested water.

2. Methodology

2.1. Study Area

Northern region of Jordan which includes Zarqa, Irbid, Ajloun and Jerash governorates has been chosen as a study area which is located at latitude of 32°05' to 32°34'(N) and longitude of 35°38' to 36°08' (E) (Figure 1) and its elevation ranges from 300 to 1100 meters above mean sea level . The climate is characterized by rainy cooled in winter and dry hot in summer. Average rainfall ranged from 140 mm/yr in Zarqa area to 582 mm/yr in Ajloun (JMD, 2006). The general specifications of the study area are listed in Table (1).

Zarqa city is classified as an industrial region with high population and heavy traffic volume, and it is the most environmentally pressured area in Jordan. Most of polluting industries including the Phosphate and Jordan Petroleum Refinery are located in this region. The area is also affected by emissions from Al-Hussein thermal power plant, and dust from brick and stone quarries. For these reasons, significant deterioration in air quality occurred, which causes accumulation of contaminants on roofs, land and streets (JEW, 2007). Irbid, Ajloun and Jerash governorates are classified as rural areas with low population density and very limited industries.

2.2. Data Collection and Analysis

Ninety samples of collected rain water from various storage tanks in these four governorates (Zarqa: 22; Irbid:

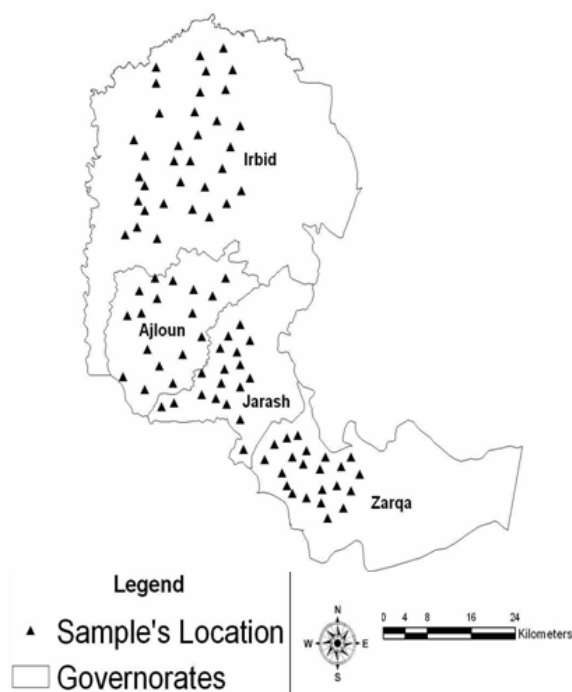


Figure 1. Study Area location.

Table 1. General characteristics of the study area (JMD, 2006, DOS, 2006).

parameter	Zarqa	Irbid	Jerash	Ajloun
Main Economic Activity	Industrial	Agricultural	Agricultural	Agricultural
Average rainfall (mm/yr)	140	455	470	582
Evaporation (mm/yr)	2520	2052	2200	1900
Average max temperature	25.5	23.03	23.1	18.2
Average min temperature	11.9	12.6	12.7	10.2
Population (thousands)	834	996	168	129
Area (Km ²)	4761	1572	410	420
% of Jordan's area	5.4	1.8	0.5	0.5

34; Jarash: 18 and Ajloun: 16) (Figure 1), were taken and analyzed for quality parameters (pH, alkalinity, Hardness, Turbidity, TDS, COD, NO₃, NH₄, PO₄, Pb, Fe, Cr). Additionally, these samples were tested for contamination of biological and microbiological contents. TCC, E.Col. and FC bacteria tests were carried out at Al Al-Bayt University laboratories according to standard methods for water and waste water examination [APHA, 1998]. Multiple tube fermentation technique sections 9221- B, E, and F was used to determine Total coliform, Fecal coliform, and E. Coli groups respectively [APHA, 1998]. The determination of heavy metals was carried out using the flame atomic spectrophotometer as described in the standard methods [APHA, 1998].

Results of analysis were further compared with valid quality guidelines to evaluate water suitability for drinking and irrigation purposes.

The investigated storage tanks were either underground or above-ground tanks and in some cases are constructed as part of the building, or may be built as a separate unit located at a distance from the building. Most of these tanks receive rainwater from roof tops, streets and catchment yards. Tanks vary in their sizes from 5 m³ to more than 60

m³ for private households and dwelling, but could reach 120 m³ for larger buildings and institutions. Water can be easily extracted through a tap just above the tank's base or by water pump. This has made surface tanks popular in rural households for drinking water and irrigation. Usually the tank is made of concert, reinforced concrete, and bricks or excavated in rocks while the inner surfaces of tank are lined with cement. Roofs made with reinforced concrete usually have waterproofing course on the surface as a finishing layer. The waterproof course is done with a small slope towards the down take pipes. If there is no waterproofing layer, the roof itself is sloped with average rate of 1.5%.

In order to eliminate the effect of solids settlement, samples were taken from different depths of the tanks. The stored water includes all harvested rainwater during winter season, so that collected samples are considered representative for the whole year rainfall. The ninety samples were taken during the period of October 2006 - May 2007

In areas where public sanitary service does not exist, wastewater disposal is practiced by means of septic tanks or pits that are located also within the boundary of the residences where sewage could leak and reach the stored water, so this parameter is considered as a possible source of water contamination.

In addition to the assessment of water quality, this study investigated other conditions that could affect stored water quality. These conditions included: location of the storage tanks, type of catchments surfaces, type of tank's construction, and the availability of sanitary systems. In order to investigate these conditions, a questionnaire was distributed to 120 household owners including questions about quantifying the importance of the above mentioned conditions and other issues in regard to public awareness for rain water harvesting.

3. Results and Discussion

3.1. Suitability of Collected Water for Drinking Purposes

Table (2) illustrates the average values of measured parameters to evaluate water suitability for domestic purposes. In regard to alkalinity, Hardness, Turbidity, TDS, COD, NO₃, NH₄, PO₄, and Fe parameters, all samples comply with Jordanian Drinking Water Standards (JDWS). pH, Pb, and Cr samples exceeded the JDWS by 10%, 6.7% and 4.5% respectively.

The analyses show that 55%, 40% and 15% of samples contained detectable values of total coliform, Fecal coliform and E.Coli, respectively.

These results indicate that the collected water is heavily contaminated with microbes, so that it becomes unsuitable for direct drinking purpose. For this reason the suitability of collected water for drinking should not be taken for granted.

3.2. Suitability of Collected Rain Water for Irrigation

In order to evaluate the suitability of collected water for irrigation purposes, the results of analyses are compared with the strictest regulations (irrigation of crops that are eaten raw). The results indicate that the water complies in its physical, chemical and biological characteristics with

WHO and Jordanian standards for reclaimed water (table 2).

Table2. Suitability of collected water for drinking and irrigation purposes.

Parameter	Units	Min.	Max.	Average	Max. Level mg/l JDWS	Reclaimed water standards (JS 893/2002)
pH	-----	7.1	8.9	7.96	6.5-8.5	6-9
Alkalinity	mg/l CaCO ₃	22	250	65.09	-----	-----
Hardness	mg/l CaCO ₃	16	352	108.18	500*	-----
Turbidity	NTU	0.1	4	0.7	5*	10
TDS	mg/l	26	393	138.47	1500*	1500
COD	mg/l	6	142	34.78	*	100
NO ₃ -N	mg/l	0.20	8.10	1.56	70*	30
NH ₄ -N	mg/l	0	0.1	0.06	0.5	-----
PO ₄	mg/l	0.23	4.41	1.27	-----	-----
Lead	mg/l	0.00	0.18	0.01	0.01	5
Iron	mg/l	0.00	0.338	0.01	1.0*	5
Chromium	mg/l	0.00	0.0988	0.012	0.05	0.1
TC	MPN/100ml	<2.2	40	19.6	-----	-----
Fecal Colif.	MPN/100ml	<2.2	15	5	0	≤1000**
(E.Coli)	MPN/100ml	<2.2	9	4.3	0	100

* In the absence of a public water source of better quality

** Source: (WHO, 1989).

3.3. Variation of Water Quality According to the Location

Average values of measured parameters in each location are presented in Table (3). The results indicated that there is a significant variation in water quality depends on the area characteristics. This result complies with the findings of other studies (Vazquez *et al.* 2003, and Abbas *et al.* 1993). Weather conditions, industrial, urban or agricultural activities, environmental cleanness, rainfall intensity, life style, and public attitude could be the reasons behind this variation.

Since that only 73 % of Zarqa governorate is served by public sanitary sewer system (WAJ, 2006), the present of cesspools and septic tanks result in further contamination of soil and subsurface water. All these parameters explain the high concentration of contaminants in samples taken from Zarqa region. A strong correlation is found between the intensity of rainfall and the contamination degree of harvested rainwater (Jiries *et al.* 2002), which is considered an additional reason of lower water quality in Zarqa governorate, where rainfall is less than 140mm/yr. Irbid, Ajloun and Jerash governorates had lower concentrations of heavy metals, hardness, and turbidity, but bacteria were found in collected samples because these governorates are classified as rural areas (low population density and very limited industries)

The public sanitary sewer service covers only 29% of Ajloun governorate population, while the remaining population (71%) depends on septic tanks and cesspools to manage their domestic wastewater which could be the source of high concentration of COD, NO₃ and biological contaminants found in the collected samples. Agricultural activities in Ajloun governorate is the reason for the high concentration of nitrogen and phosphor constituents in the collected samples. Type of soil and the cleanness of the

Table 3. Pollutants concentration for different governorates.

Governorate	Unit	Zarqa	Irbid	Jerash	Ajloun
pH range average	--	7.8-8.9 8.12	7.1-8.1 7.64	7.3-8.1 7.62	7.7-8.7 8.26
Alkalinity	mg/l CaCO ₃	92-250 143.4	22-67 44.8	31-72 48.33	51-101 76.82
Hardness	mg/l CaCO ₃	178-352 224.6	16-82 55.4	56-111 73.71	92-171 137
Turbidity	NTU	0.7-4 1.7	0.1-0.8 0.4	0.7-1.5 1.14	0.2-0.74 0.45
TDS	mg/l	198-393 251.4	26-117 79	72-155 110.86	135-205 169.36
COD	mg/l	55-142 80.5	16-37 21	6-24 13	21-57 36
NO ₃ -N	mg/l	3.5-8.1 4.95	0.35-1.2 0.76	0.2-1.1 0.66	1.6-2.4 2.08
NH ₄ -N	mg/l	0-0.1 0.08	0-0.08 0.02	0-0.08 0.06	0-0.1 0.07
PO ₄	mg/l	0.23-1.3 0.90	0.85-1.5 1.15	0.95-1.65 1.3	1.3-4.41 1.78
Pb	mg/l	0-.18 0.04	0-0.1 0.026	0-.05 0.001	0-0.01 0.005
Fe	mg/l	0-0.33 0.055	0-0.1 0.02	0	0
Cr	mg/l	0-0.098 0.037	0-0.07 0.015	0	0-0.06 0.01
TC	MPN/100ml	0-40 29.33	0-23 8.2	0-31 7.2	0-28 23.03
Fecal Colif.	MPN/100ml	0-15 8.3	0-7 3.3	0-11 3.7	13-0 5.1
(<i>E.Coli</i>)	MPN/100ml	0-9 6.1	0-6 2.3	0-9 2.4	9-0 3.2

catchment area affect the turbidity and the concentrations of other parameters. The main source of lead (Pb) is the gasoline fuel, and its concentration in harvested water is mainly affected by the traffic volume in the area and the presence of fuel stations near storage tanks.

3.4. Effect of the Type of Catchment's Area

In houses, rainfall is usually collected from two catchments areas: house roofs and /or the land around the storage tank, so that the water quality is strongly affected by the cleanness of these areas. Roofs made of reinforced cement concrete (RCC), or roof tiles are the most common roof types in Jordan. Roofs are contaminated as a result of ambient air pollution and the emitted smokes from fireplaces and chimneys. Rooftops are usually free of organic contaminants, a reason that very low concentrations of COD and NO₃ are found in samples taken from tanks that are fed directly by these roofs. Land catchments area is exposed directly to contamination sources. Possible sources of contaminants include fertilizer, pesticides, chicken and livestock manure, dissolved minerals, sediments, sewage, decaying plants, algae, bacteria and detergents. All these pollutants are washed with rainfall to the storage tank causing an increase in water contaminants, which result in a higher concentration of COD, NO₃ and biological contaminants.

It was found, for the samples collected from rooftop catchments, that the average concentrations of TC, FC and *E.Coli*. are: 6.4, 2.5, and 2.2 MPN/100ml respectively, while for the samples collected from the land catchments of the storage tanks, the average concentrations for the same parameters are: 24.5, 11.2, and 5.1 MPN/100ml, respectively.

The presence of lead, Pb, iron, Fe, and chrome, Cr, in samples taken from tanks that receive water through land is attributed to the contamination of land catchments by

these elements. For all quality parameters, harvested rainwater from rooftops have better quality than water collected from the catchment areas as illustrated in table 4. Similar results are reported by Zunkel *et al.* (2003) and Zhu *et al.* (2004) as they found that the quality of harvested water is strongly affected by the contamination of the catchments area.

Table 4. Water quality according to the type of the catchment area.

parameter	Land catchment	Top roof
pH	8.32	7.81
Alkalinity	132.3	54.45
Hardness	219.6	83.8
Turbidity	1.4	0.65
TDS	254.4	112.5
COD	80	37
NO ₃ -N	4.015	1.29
NH ₄ -N	0.1	0
PO ₄	4.03	0.5
Pb	0.028	0.01
Fe	0.038	0
Cr	0.032	0.01
Colif. MNP/100ml	24.5	6.4
Fecal Colif.	11.2	2.5
(<i>E.Coli</i>)	5.1	2.2

3.5. Effect of Tank's Type on Water Quality

Storage tanks are usually constructed either by using concrete or they are excavated in rocks (cistern). A difference in water quality is also found in samples depending on the type of these tanks.

The variation in quality parameters (table 5) can be reasoned according to the path of rain water until storage.

Table 5. Water quality according to the tank's type.

parameter	Concrete tanks	Rock tanks
pH	7.81	8.1
Alkalinity	58	97.53
Hardness	95.69	154.59
Turbidity	0.46	1.23
TDS	118.61	191.29
COD	37	80
NO ₃ -N	1.35	2.62
NH ₄ -N	0	0.1
PO ₄	0.7	3.7
Pb	0.01	0.013
Fe	0	0.022
Cr	0.013	0.02
TC	9.7	25.4
Fecal Colif.	3.3	7.2
(<i>E.Coli</i>)	2.7	5.6

Most of concrete tanks are included in house-buildings, while rock storage tanks are usually located in yards or gardens. As a sequence of that, concrete tanks receive water directly from roof tops, while rock storage tanks receive water that passes through land surrounding these tanks. For this reason, the higher contamination of

rocky storage tanks (cistern) compared to that of rooftops is attributed to the contamination of the catchment area.

The concentration of microbes TC, FC, and E-Coli in samples taken from cisterns are found to be higher (25.4, 7.2, 5.6 MPN/100ml) than that in samples taken from concrete tanks (9.7, 3.3, 2.7 MPN/100ml).

3.6. Effect of The Sanitary Service on Water Quality

The presence of septic tanks in near distance to the rainwater tanks within the boundary of residences was also considered as a potential risk for quality of harvested water. The local regulatory authority, commonly the local municipality, issues a construction permit; but after the system is installed, there is no further oversight or requirement that it is cared for. System owners are not likely to repair or replace aging or otherwise failing systems unless in sewage backup, seepage pooling on lawns, or targeted monitoring that identifies health risks occur. In most cases, these systems are installed and largely forgotten until problems arise. If any deterioration in the system of septic tank occurs, wastewater will reach to the adjacent storage tank of harvested rainwater. Table 6 shows that all considered quality parameters, (including microbial indicators) have higher concentration in samples that are taken from areas where septic tanks are used compared to samples collected from areas with public sanitary service.

Table 6. Water quality according to the availability of sanitary service.

parameter	Concrete tanks	Rock tanks
pH	8.0	7.8
Alkalinity	82.33	63
Hardness	130.74	104
Turbidity	0.92	0.57
TDS	151.81	121.67
COD	69.5	35
NO ₃ -N	2.26	1.69
NH ₄ -N	0.1	0
PO ₄	3.0	0.8.
Pb	0.016	0.014
Fe	0.014	0
Cr	0.018	0.008
Colif. MNP/100ml	21.6	16.3
Fecal Colif.	6.37	5.1
(E.Coli)	4.5	3.6

4. Summary and Conclusions

Rain water harvesting is an attractive option for increasing available water resources, especially in the drought and arid regions. The results of this research indicated that the collected water is heavily contaminated with microbes, so that it becomes unsuitable for direct drinking purpose. Thus, this water might be used for irrigation purposes. The harvested water is valuable

source for irrigation of gardens, landscapes, fruits and crops.

The research results showed that there are variations in water quality according to the location. Harvested water in Zarqa has lower quality than water harvested in Ajloun, Jarash and Irbid because of the industrial activities in this governorate.

The quality of harvested water is found to be strongly affected by the catchment area. Harvested water from rooftops has better quality than the water harvested from the surrounding areas.

The influence of Tank's type on quality of harvested water was also investigated in this research. Concrete tanks have better water quality than cisterns. It was found that the variation in quality parameters can be reasoned according to the path of rain water until storage concrete tanks receive water directly from roof tops, while rock storage tanks receive water that passes through land surrounding these tanks

The possible impact of septic tanks on water quality was also investigated to determine whether these septic tanks pose a threat to water quality. It was found that areas served with sanitary systems have better quality of harvested water than areas with septic tanks.

Finally, public awareness has an important role in collected rain water management. Education, training, and financial supports are needed to encourage people to consider importance and quality of collected water. Clean environment produce clean water. Several environmental conditions should be taken into consideration to improve water quality such as proper design, operation and periodical maintenance of collection systems, cleanness of catchment area, and protection of collection systems against septic tanks leakages.

5. Recommendations

In order to have better quality of harvested water, it is recommended that:

1. Rooftop and catchment area must be cleaned before the rainfall season.
2. Locating cesspools at a far distance from the storage tanks to prevent any leaching of containments.
3. Water samples should be collected and analyzed on regular basis from the storage tanks before using the water for drinking purposes.
4. Adding some disinfecting agents such as chlorine might help in reducing the risk of biological contamination.

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Ordovician Invertebrates from Jebel Qamar South, Dibba Zone, United Arab Emirates

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Abstract

A limited invertebrate fauna have been collected from the detached exotic blocks in the Dibba zone at Jebel Qamar South, United Arab Emirates. The Receptaculitacea species *Cyclocrinus multicavus*, the Orthoceratidae *Orthoceras* sp., and the Nileidae *Nileus emiratus* n. sp., have been identified. According to this fauna, a Middle Ordovician age could be assigned to the upper part of the Rann Formation and the lower part of the Ayim Formation, from which the described specimens have been obtained. The fauna indicates a deposition in a shallow shelf environment with open circulation. The prevailing palaeoclimatic conditions in the area in connection with the widespread Late Ordovician Saharan glaciations postulate that the nileids and the receptaculitids probably tolerated wide range of temperature changes.

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Keywords: Ordovician, Jebel Qamar, Nileids, Receptaculitids, United Arab Emirates.

1. Introduction

Very little is known about invertebrate macrofossils of Early Paleozoic sequence of the Oman Exotics terrains because of scarcity of fossils. Hudson et al. (1954) reported *Cruziana* tracks and un-identified trilobites from the Rann Grits and Shales of Jebel Qamar, and assigned the succession to the Middle Ordovician age. Robertson et al. (1990) recorded the presence of orthocones, bone material, fish teeth, and broken fish scales from the base at the Ayim Formation of the Lower Paleozoic sequence at the southeast end of Jebel Qamar South. Orthocones and echinoderm fragments also occur in the upper part of the formation. A Devonian age was assigned to the Ayim Formation based on this fauna.

The intent of this paper is to record, and describe Lower Paleozoic assemblage from the substratum of the Jebel Qamar South in the Dibba Zone of the United Arab Emirates. Knowledge of these fossils is highly desirable since the stratigraphic interval which they characterize belongs to a poorly defined stratigraphic sequence. Furthermore, the study of these taxa will shed light on Lower Paleozoic paleoenvironments and on tectonic history of the Oman Exotics.

2. Lithostratigraphy

Throughout the Oman Mountains, large detached exotic blocks of Ordovician to Triassic age occur in a sedimentary mélange (U. Cretaceous) between the

Hawasina Complex (U. Triassic – M. Cretaceous allochthonous basinal sediments) thrust sheets and the Semail Ophiolites (M. Cretaceous allochthonous oceanic crust). These exotic blocks are represented in the Dibba Zone by Jebel Qamar North and Jebel Qamar South (Long. 56° 02' E. & Lat. 25° 25' N.), which are both large blocks (16 km. by 11 km.) floating in the sedimentary mélange (Hudson et al. 1954; Alleman & Peters, 1972; Glennie et al. 1973; Sealer et al. 1983; and Robertson et al. 1990) (Fig.1).

The sedimentary sequence of Jebel Qamar was first studied by Hudson et al. (1954) who recorded the following five rock units:

- 5- Shamali Limestone (? 200m.), Upper Triassic to Rhaetic. Limestones, sandstones and marls. With *Dicerocardium*.
- 4- Ummali Dolomite (750m. +), ? Triassic. No fauna.
- 3- Qamar Limestone (500m. +), Middle Permian. With *Parafusulina*, *Neoschwagerina*, corals and brachiopods.
- 2- Asfar Beds (150m.), Permian. Sandstones and limestones. With *Fenestella*, *Tachylasma*, productids and spiriferids brachiopods.
- 1- Rann Grits and Shales (250m.), Middle Ordovician. With *Cruziana* tracks and trilobites.

Robertson et al. (1990) studied Lower Paleozoic substratum of the Oman Exotics in the Dibba Zone at the southeast end beneath the unconformity at the base of the Asfar Beds. Sequences exposed in mélange blocks were measured and correlated to give a composite succession (Fig. 2). They introduced the Ayim Formation (condensed shelf deposition) of Devonian age between the underlying Rann Formation and the overlying Asfar Formation. They also concluded that the thicknesses of individual rock units given by Hudson et al. (1954) included what Robertson et

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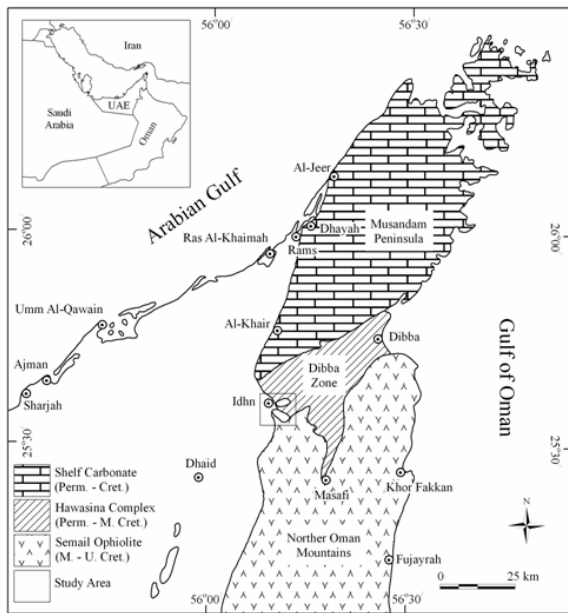


Figure 1. Geologic map of the Musandam Peninsula and Dibba Zone, United Arab Emirates (modified after Searle et al., 1983) and location of study area.

Searle & Graham (1982) interpreted that the unconformable overlying Permian- Triassic massive limestone of the Jebel Qamar North and South as a carbonate buildup on a horst of basement subsequently rifted away from the continental platform .

3. Material

Owing to the particular interest of the Paleozoic sequence exposed beneath the Jebel Qamar South in the Dibba zone, the Rann Formation and the Ayim Formation, which are both poor in fossil content, have been studied and sampled for invertebrate fossils during several seasons (1980-1994). Two specimens of cyclocrinids were collected from the top of thinly-bedded, shaley, medium grained quartzose sandstone of the Rann Formation. One specimen of nileid trilobites and several specimens of orthoceratid nautiloids were collected from the lower part of the Ayim Formation which consists of finely-laminated, thinly-bedded brown shale, argillaceous calcilitite and calcareous siltstone. The orthoceratids are preferentially oriented in the succession.

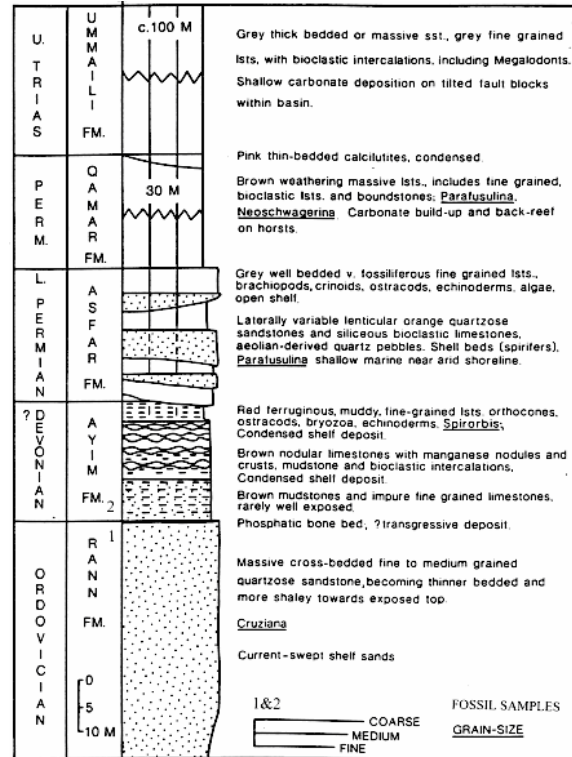


Figure 2. Composite succession of the palozoic sediments exposed in exotic blocks in the vicinity of jebel Qamar. Position of described fossils is indicated by number 1, Cyclocrinus; and number 2. Orthoceras and Nileus (Modified from Robertson et al ., 1990).

3.1. Systematic Palaeontology

The terminology used in the present study is mainly consistent with “Treatise on Invertebrate Paleontology” (Harrington et al., in Moore 1959; and Teichert et al., in Moore 1964), and in line with Nitecki 1969 a,b and Nitecki 1972 and Fisher & Nitecki 1982.

Repository of the described specimens took place in the Hashemite University, Zarqa, Jordan.

Abbreviations: HUEES: Hashemite University Earth and Environmental Sciences. P: Palaeontology. R: Receptaculitids. N : Nautiloids. T : Trilobites.

- Class Receptaculitaphyceae WEISS, 1954
- Order Receptaculitales JAMES, 1885
- Family Receptaculitaceae EICHWALD, 1860
- Genus Cyclocrinus STOLLEY, 1896
- Cyclocrinus multicavus STOLLEY, 1896

Figures. 3, 4

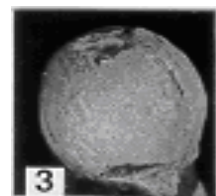


Figure 3. Globose thallus, broken top; 1X.

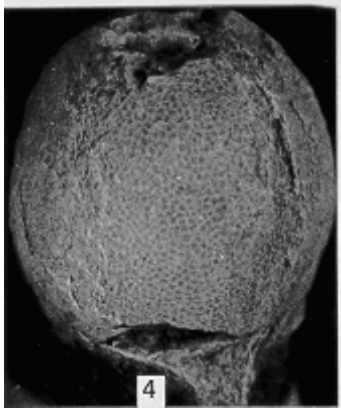


Figure 4. The same as Fig. 3 enlarged, densely joined meroms; 3X.

3.2. Material: Two thallae, HUEES – PR 1- 2.

Remarks: The receptaculitids are problematic Palaeozoic organisms, which were placed by different authors into different animal and plant groups. This group has recently been considered to be calcareous algae, belonging to the Dasycladales (Kesslings & Graham, 1962, Nitecki 1969 a, b, 1972 b), but its taxonomic position is still uncertain (Nitecki & Rietschel, 1985), although they are often well preserved.

The cyclocrinids are also of uncertain position. They were considered by Pia (1926, 1927) as a tribe "Cyclocrineae" within the thallophyte family Dasycladaceae. Then they were placed by Nitecki (1972a) as the tribe "Cyclocriniteae" into the Receptaculitaceae.

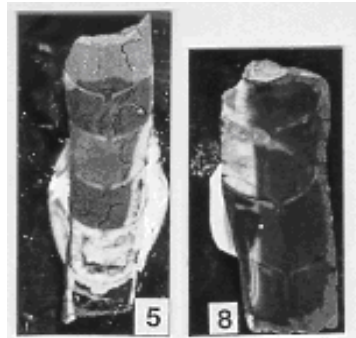
Description: The better preserved thallus HUEES-PR1 described in the present study is globose, slightly compressed due to compaction, with the larger diameter of 21.4 mm and the smaller one of 18.4 mm, height about 20 mm; the top, which becomes inflated after a slight flexure, is broken in our specimen; only the base of the flexure is preserved. The surface of the thallus is covered regularly with densely joined meroms (Fig. 3). Distal plates are not preserved; excavated polygonal outer faces of the meroms are 0.3-0.5 mm in diameter.

The Emiratian specimen (Fig.3-4) is comparable to the specimens described by Stolley (1896) and determined by Neben & Krueger (1979) in dimension and shape of thallus and in size, shape, and arrangement of meroms. Therefore, they have been assigned to *Cyclocrinus multicavus* STOLLEY, 1896.

Discussion: Stolley (1896) described the *Cyclocrinus multicavus* from rocks belonging to the upper parts of Ordovician.

Therefore, the Rann Formation from which our specimens are obtained can be assigned to Middle to Late Ordovician age.

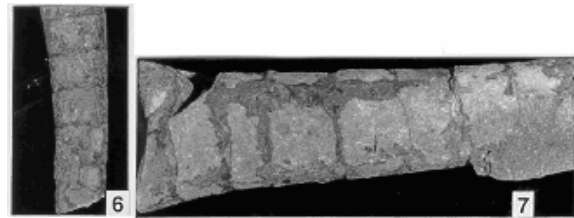
Phylum	Mollusca Linneus
Class	Cephalopoda Cuvier
Subclass	Nautiloidea Agassiz, 1847
Order	Orthoceratida Kuhn, 1940
Family	Orthoceratidae M'Coy, 1844
Genus	<i>Orthoceras</i> Brugier, 1789
	<i>Orthoceras</i> sp.



Figures 5, 8: *Orthoceras* sp, Figure 5. Sagittal section showing strongly curved septa, central tubular siphuncle, and orthochoanitic septal necks; HUEES-PN 1; 1,4 X, Figure 8. Sagittal section, tubular siphuncle; HUEES-PN3; 1,5X.

Material: Five phragmocone fragments preserved as internal moulds (HUEES, PN 1-5).

Description: The phragmocone is, a small slender orthoconic longicone (Fig.6-7) with more or less circular cross section and septa that are strongly curved.



Figures 6, 7. Figure 6. Orthoconic phragmocone fragment showing wide and equal spaced septa; HUEES-PN1; 1,4X. Figure 7. Phragmocone fragment widened anteriorly; HUEES-PN2; 2X.

The cameral lengths range from 1/3 to 2/3 of diameter. In a length of 5 cm of the phragmocone, 8-9 septa occur. Siphuncle central and tubular make about 7-8% of the diameter of the phragmocone. Sptal necks orthochoanitic is with a length of about 0.7 mm (Figs.5, 8).

The studied phragmocone fragments did not contain cameral or siphuncular deposits.

Discussion: The studied specimens are internal moulds of phragmocone fragments. Therefore, they could not be assigned to certain species, but the general shape of the phragmocones, the central tubular siphuncle, the orthochoanitic septal necks, and the lack of cameral and siphuncular deposits indicate that these specimens belong to orthoceratid cephalopods, particularly to the genus *Orthoceras*. The specimens are most similar to the specimens described by Stait & Flower (1985) as *Orthoceras* sp. from the top of the Karmberg Limestone (Late Whiterockian to Early Chazyan) at Sunshine Road in the Florintine Valley, Tasmania, Australia.

specimens in this study have also similarities with the specimens described by Frey (1995) from the Tyrone Limestone (Rocklandian, Middle Ordovician), central Kentucky, USA., as *Pojetoceras floweri* FREY, but this species has cameral and siphuncular deposits, which are absent in the specimens described in the present study.

Remarks: As the Emiratian specimens described here (Figs.5-8) and the specimens described by Stait & Flower (1985) from Tasmania, Australia as *Orthoceras* sp. are closely similar and belong most probably to the same species, and the Australian specimen is of Middle

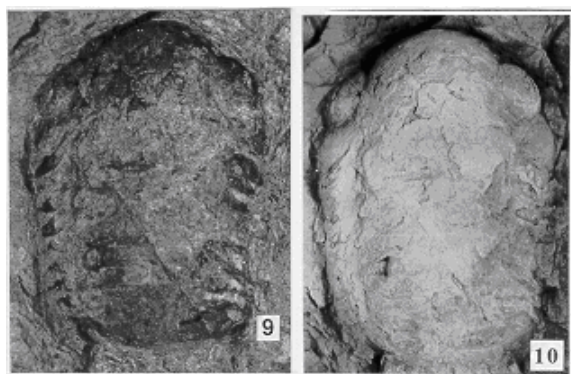
Figures. 5, 6, 7, 8

Ordovician age. Therefore, the Emiratian specimens can be assigned a Middle Ordovician age.

Stratigraphic and geographic distribution: Middle Ordovician Karmberg Limestone Tasmanian (Australia) and the Ayim Formation, Jebel Qamar South, United Arab Emirates.

Class	Trilobita WALCH, 1771
Order	Ptychopariida SWINNERTON, 1915
Suborder	Asaphina SALTER, 1864
Superfamily	Cyclopygacea RAYMOND, 1925.
Family	Nileidae ANGELIN, 1854
Genus	<i>Nileus</i> DALMAN, 1827
	<i>Nileus emiratus</i> n. sp.

Figures. 9, 10



Figures. 9, 10. *Nileus emiratus* n. sp.; holotype; HUEES-PT1, Figure 9. Semireniform cephalon thorax of 8 segments with wide axis; 1X, Figure 10. Very wide glabella, large eyes and rounded genal angles; the same as Fig. 7; 1X.

Material:

One specimen preserved as internal mould.

Derivatio nominis: After the state of the United Arab Emirates.

Locus typicus: Jebel Qamar South, the Dibba zone. United Arab Emirates.

Stratum typicum:

Lower part of the Ayim Formation, Middle Ordovician.

Holotype : HUEES-PT 1, Figs. 7-8 (of a single specimen).

Paratypes:

none.

Stratigraphical distribution:

Ordovician.

Geographical distribution:

United Arab Emirates.

Depository:

Dept. of Earth and Environmental Sciences of the Hashemite University, Zarqa, Jordan.

Diagnosis:

The cephalon is semi- reniform, almost without border, and with round genal angles extending backwards beyond anterior margin of the axis.

Dimensions of the holotype: Length of skeleton ~ 64 mm, width about 43 mm, length of glabella ~ 18 mm, width of glabella 22 mm, length of thorax 33 mm, length of pygidium ~ 13 mm, width of pygidium ~ 33 mm, palpebral lobe 10 mm long, librigenae ~ 9 mm long.

Description: Dorsal skeleton strongly and evenly convex transversely, rounded at both ends (Figs.9-10); cephalon semireniform, rounded genal angles extended backwards beyond axial anterior margin without visible border on the mould and also without occipital furrow; glabella very

wide, parallel sided and slightly and evenly convex, without lateral furrows (Figs.9-10), with length a little bit less than width and declined steeply anteriorly; eyes large crescentic; palpebral lobes semi-elliptical and large, with length half that of cranium, separated from glabella only by indistinct axial furrows; thorax of 8 segments, with parallel sided slightly and evenly convex wide axis making about $\frac{3}{4}$ of thorax width; semicircular convex pygidium with indistinct axis, smooth, and length making about 40% of width.

Remarks:

Fortey and Chatterton (1988) presented a new phylogenetic classification of the suborder Asaphina. These authors, who studied several Nileid protaspides, placed the Family Nileidae, which was earlier included in the superfamily Asaphacea, in the superfamily Cyclopygacea. The suborder Asaphina presumably originated in the Middle Cambrian. Some taxa of the Asaphina did not survive the Middle Ordovician. The rest, including the family Nileidae, which began in the Early Ordovician, survived until the end of this period. The disappearance of this diverse and worldwide distributed group at the end of the Ordovician Period is difficult to explain, but it could be, as postulated by Fortey & Chatterton (1988), connected with a change in oceanic circulation which has affected the life of the planktic asaphoid larvae.

Discussion:

Several species of the genus *Nileus* have been described from beds ranging in age from Early to Late Ordovician in Europe, N-America and Asia. The Emiratian specimen shows similarities in cephalic features with the genus *Symphysurus* but the glabella of *Symphysurus* is more convex and its axis is also more convex and narrower than that of the species described in the present study. It has been placed in the genus *Nileus* because it has, like most species belonging to this genus a large, a very wide, slightly and evenly convex glabella, large crescentic eyes, and a wide evenly convex axis with indistinct furrows. It can be compared with the type species *Nileus armadillos* from Sweden, but *N. emiratus* has larger librigenae, larger palpebral lobe; and is in general larger. It can be also easily differentiated from *N. walcotti* from China (Endo, 1932, Zhou et al. 1998 a,b); *N. emiratus* is larger and has larger palpebral lobes and larger librigenae. It can be also distinguished from *N. exarmatus* and *N. orbiculatoides* from Sweden by the larger librigenae and the rounded cranium in contrast to the subangular one of those species. It differs also from *N. huanxianensis* from China by (Zhou et al. 1982, Zhou & Dean 1986) in its much larger size, larger palpebral lobes and larger librigenae. *N. huanxianensis* has, on the internal mould, a weak medial glabellar ridge which is absent in *N. emiratus*. *N. emiratus* differs also from *N. porosus* from Spitzbergen by its larger palpebral lobes and larger librigenae. *N. porosus* has punctae on the cranium, and *N. emiratus* has no such punctae.

4. Discussion and Conclusion

Trilobites occur in a variety of marine lithofacies. They are abundant in limestones, shales and sandstones

representing deposition in shallow, normal shelf environments with open circulation.

Whittington & Hughes (1972) delineated four Lower Ordovician faunal provinces which have been defined and named after characteristic endemic families or genera. The bathyrid province extends over most of North America, Greenland, western Norway, Ireland, Scotland, Spitzbergen and The Siberian platform. The asaphid province occupies the Balto- Scandia and the Urals. A *Selenopeltis* province covers England, southern and Eastern Europe and North Africa.

The fourth province consists of a less well- known fauna and is confined to South America and Australia. It is named after *Asaphopsis* . By Caradocian times, only the *Selenopeltis* province persisted whereas the other three provinces had merged into a single remopleuridid province.

Genera and species of the Family Nileidae have been recorded from Lower to Upper Ordovician strata of different locations. The genus *Nileus* occurs in Sweden, Spitzbergen, China, North America, South America (Fortey 1975; Zhou et al. 1989, 1998) and the United Arab Emirates. This wide geographic distribution of the Nileid fauna indicates their low endemism.

During Late Ordovician times there was a pole situated where now the Sahara Desert is. A short but widespread glaciation is known from later Ordovician, centered on this pole. The central Arabian region lay at the northern edge of the widespread Saharan glaciation (Mclure, 1978 ; Vaslet , 1989 ; Beydoun, 1993).

In the United Arab Emirates, *Nileus* occurs in a thin-bedded, shaley, fine to medium-grained current-swept shelf sandstone of the upper Rann Formation . This detrital succession indicates deposition in a cold, carbonate deficient, shallow shelf environment. Therefore, it is assumed that the Nileid community tolerated a wide range of temperature changes during Ordovician times .

Robertson et al. (1990) assigned an Ordovician age to the Rann Formation and a Devonian age to the Ayim Formation. The recorded and described cyclocrinid, orthoceratid and Nileid species indicate Middle to Late Ordovician age and a shallow inner shelf marine environment of the Raan Formation and the lower part of the Ayim Formation at the southeast end of Jebel Qamar South.

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التقديم

بعون من الله وبتوقيقه، يسعدني أن أقدم لكم العدد الأول من المجلد الأول من المجلة الأردنية لعلوم وهي مجلة علمية ، الأرض والبيئة (Jordan Journal of Earth and Environmental Sciences) عالمية محكمة و مفهروسة، تصدر عن اللجنة العليا للبحث العلمي في وزارة التعليم العالي والبحث العلمي في المملكة الأردنية الهاشمية. ويشرف على إعداد و نشر هذه المجلة عمادة البحث العلمي والدراسات العليا في الجامعة الهاشمية.

تحرص هيئة التحرير للمجلة الأردنية لعلوم الأرض والبيئة أن تكون مرجعاً مهماً للدارسين والباحثين، يستتبرون بما ستتضمنه من بحوث أكاديمية أصيلة ودراسات علمية عميقة في شتى موضوعات علوم الأرض والبيئة. وتتسع هيئة التحرير ومن خلال دعم وزارة التعليم العالي والبحث العلمي والجامعات الأردنية كافة المتواصل أن تصل هذه المجلة إلى مرتبة متقدمة ضمن المجالات العلمية العالمية المتخصصة في هذا المجال.

إننا نتمنى أن تشكل هذه المجلة قاعدة أساسية ترفد عملية النشر والبحث العملي في مجالات علوم الأرض والبيئة المتعددة، وتضع ما توصلت إليه الأبحاث العلمية المنشورة في المجلة في متناول أيدي الباحثين والمتخصصين. وتنشر المجلة مقالات الأبحاث العلمية التي تتسم بالجدة والأصالة، إضافةً إلى الملاحظات الفنية و التقنية ومقالات المراجعة لموضوعات حيوية و تهم الدارسين و الباحثين في مختلف حقول علوم الأرض والبيئة. ويجري تحكيم كل ما تنشره المجلة من قبل محكمين من ذوي الاختصاص والخبرة. يشتمل العدد على خمسة مقالات أبحاث أصيلة تعالج جوانب متعددة في علوم الأرض والبيئة.

أتقدم بالشكر العميق لأعضاء هيئة التحرير وأعضاء الهيئة الاستشارية الدولية للمجلة الذين قدموا النصح والمشورة لإصدار هذا العدد من المجلة. أما أتقدم بالشكر والعرفان للزملاء الذين قاموا بتحكيم الأبحاث على الوقت و الجهد الذي بذلوه في مراجعة وتحكيم هذه الأبحاث الامر الذي أدى الى تحسينها وتطويرها. وكذلك أتقدم بالشكر لكافة الزملاء للذين تقدموا بأبحاثهم للمجلة، سواء ما تم قبوله منها أو من لم يقبل، حيث أن أبحاثهم هي العنصر الأساسي في إصدار هذه المجلة.

وختاماً، و بالنيابة عن هيئة التحرير و بالأصالة عن نفسي، نرجو أن نكون وفقنا على تقديم كل ما هو مفيد لكافة الباحثين والعاملين في ميادين علوم الأرض والبيئة المختلفة من خلال هذه المجلة، أملين من الباحثين والقراء الكرام عدم التردد في المساعدة وإرسال مساهماتهم واقتراحاتهم واستفساراتهم للارتقاء بهذه الدورية العلمية المتخصصة لما فيه مصلحة الجميع . والله ولي التوفيق.

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