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Mining Evaluation of Sulfur Deposits in Al-Mishraq Area Using Geostatistical Method

Muzher Jar Hassan , Ghazi Atiya Zarraq
Applied Geology Department, College of Science, Tikrit University, Tikrit , Iraq
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Corresponding Author:
Name: Muzher Jar Hassan
E-mail:
Muzheraljubury@gmail.com
ghazi.zarraq@tu.edu.iq
Tel:

ABSTRACT
The area of the study is located in northern Iraq on the western side opposite the confluence of the Tigris River with the upper Zab tributary, about 45 km southeast of the city of Mosul within the Hamrin-Makhoul zone belonging to the foothills zone within the unstable area. The area contains rocks of many formations ranging in age from the Lower Miocene to the Quaternary, and includes the formations of the Euphrates, Fatha, and Quaternary deposits. Sulfur deposits are present in the Fatha formation within the productive bed which contains three major sulfur-bearing horizons or zones separated by several heterogeneous layers of marly claystone and dolomite limestone of different thicknesses. The formation of sulfur due to the processes of reducing gypsum or anhydrite with the availability of hydrocarbons and the action of anaerobic bacteria, where hydrogen sulfide gas H2S is produced, which is later oxidized by groundwater, forming sulfur ore with the help of other factors represented by tectonic and hydrogeological factors.
The mineral reserves of sulfur deposits were recalculated and estimated using the geostatistical method, as it is one of the modern applications adopted in the Rockwork-14 program, which takes into account the location of each model in relation to the other within the mineral deposits extensions and even outside the boundaries of those extensions, which gives high accuracy and reliability about the amount of reserves depending on the group Among the important criteria, such as thickness, concentration of the ore, and density, the reserve of sulfur in the Mishraq sulfur field-1 was estimated at 121,230,554,68 tons.
The validity and suitability of using the open mine method for extracting sulfur in the study area was discussed based on a decisive and important factor, which is the stripping ratio, which determines the type of appropriate extractive method, and it was equal to 6 for the entire study area, a large value that exceeded the maximum permissible limit of 5. This method is not economically feasible due to the high extractive cost and the presence of sulfur at different depths ranging between 80-230 m as well as the presence of environmental and geological problems that hinder the use of this method in sulfur extraction.
The study was based on the data obtained for a group of (9) exploratory wells that were drilled in the region.

Introduction
The sulfur deposits are located within a anticline structure known as Mishraq Anticline located underground north of mishraq area, whose axis extends northwest-southeast, sunken from both sides within the regional direction of the folds system in northern Iraq, located west of the Tigris River at its intersection with the upper Zab tributary. The estimated reserve of sulfur deposits represents the largest known reserve in the world, ranging between (100-250) million tons of sulfur[1].
In this study, a recent data reprocessing and evaluation of sulfur deposits in the Mishraq-1 sulfur mine, which contains one of the largest sulfur reserves in the world, was conducted Sulfur deposits

are located within Fat'ha formation, which contains different facies, depending on the sedimentary cycles that formed, where the sulfur deposits are located within three zones of limestone bed with high porosity, separated by several sedimentary cycles of mudstone, marl, anhydrite, gypsum and marly limestone[2]. The presence of several combined geological, structural, hydrological and biological conditions helped to form and sulfur ore deposited, which is the presence of the subsurface of mishraq anticline structure with the presence of the source rocks represented by the presence of gypsum and anhydrite beds in the Fat'ha formation as well as the presence of several aquifer horizons flowing within the limestone layers heading from North-east towards the Tigris River, as well as the presence of anaerobic bacteria that reduce sulfur with the rise of hydrocarbon materials and gases represented by (H_2S) gas emitted from the oil reservoir, which helped to reduce the sulfur element and then this element was oxidized by the presence of underground water and provide oxygen to the deposition and formation of the sulfur element, which is deposited in the cavities and fractures formed in the limestone layers of Fat'ha formation[3].

In this study, a reassessment and estimation of sulfur ore reserves in the Al-Mishraq mine (M-1) were carried out based on 9 wells, the data for which were obtained from the Mishraq Sulfur Company using the Rockwork-14 program, and the application of the geostatistical method according to which the impact area of sulfur deposits is extended depending on the thickness and concentration value of the beds. Sulfur within the area of the extension of the field of Al-Mishraq-1. The incubating beds of sulfur deposits within the formation of the hole were identified and drawn with a cross-section for the purpose of understanding and accurately understanding the extent of these deposits.

Study area location

The Mishraq mine (M-1) is located in the northern part of Iraq, 45 km south of Mosul Governorate, at the confluence of the Great Zab with the Tigris, and on the western bank of the Tigris River. Between longitudes 59 ′ 17 ˚ 43 and 24 ′ 20 ˚ 43 and latitudes 55 ′ 00 ˚ 36 and 04 ′ 05 ˚ 36. (Fig. 1)

Geology of the study area

The study area is located within the Hemrin-Makhool zone, which belongs to the foot hill zone within the unstable region [4] and contains rocks of many formations ranging in age from the Lower Miocene to the Quaternary era [5].

The following is a description of the stratigraphic sequences from the oldest to the most recent:

• The Euphrates limestone formation (lower Miocene).

is found at different depths ranging between 179-250 m from the surface of the earth and consists of Marley limestone that contains bituminous materials in some of its parts[6]. Especially the upper ones, while some types of fossils increase in its lower parts. There is no significant heterogeneity in the lithology between the upper part of this formation and the lower part of the crater formation above it, and the surface separating them was determined by microfossils and some types of well logs[7].

• Fatah Formation (Middle Miocene):

The rocks of this formation are exposed in most parts of the region[8]. (Fig. 1), and they are the most important because they contain sulfur ore in some parts. In general, and because of the importance of this formation from an economic point of view and its extension across vast areas of Iraq, a number of researchers and oil and mining companies have taken care of it and divided it in several forms[9]. The formation in the study area consists of sedimentary cycles ranging from 10-16 cycles, where the thickness of the cycle ranges between 1-20 m and consists of a homogeneous arrangement of clay, marl, gypsum and limestone. Some of these cycles are complete and the other part is missing one or more of the four components mentioned above. The Al-Mishraq region is also characterized by the transformation of gypsum and anhydrite rocks into Recrystallized sulphureous limestone and Secondary limestone. In some parts of the region, sediments of the body and side anhydrite change to Clay [10].

• Injanah Formation (Upper Miocene):

The injana Formation is located along the southwestern edge of the region and consists of layers of clastic clay, marl and sandstone[11]

• (Quaternary sediments):

These sediments cover some areas in the region and consist of pebbles and sand of various sizes with clay lenses and the thickness of these sediments reaches 25 m in some places[12]

Geomorphologically, the study area is considered a plateau regoin, as the Mishraq region is characterized by undulating lands and low hills. One of the very important phenomena in the Mishraq region is the Karst phenomenon, which is formed as a result of the dissolution of limestone rocks, gypsum and anhydrite following groundwater and rain that lead to the formation of Depressions on the surface of the earth[13], an example of this is the sinkholes located north of the research region, which are of different diameters, in addition to the formation of subterranean channels in deeper sides than that represented in the gaps and openings of solutions as a result of the dissolution of the inner rocks, and there are cavities and inner tunnels that are formed in a manner Indirect as a result of the extraction of sulfur from the ground in a frasch method [14].

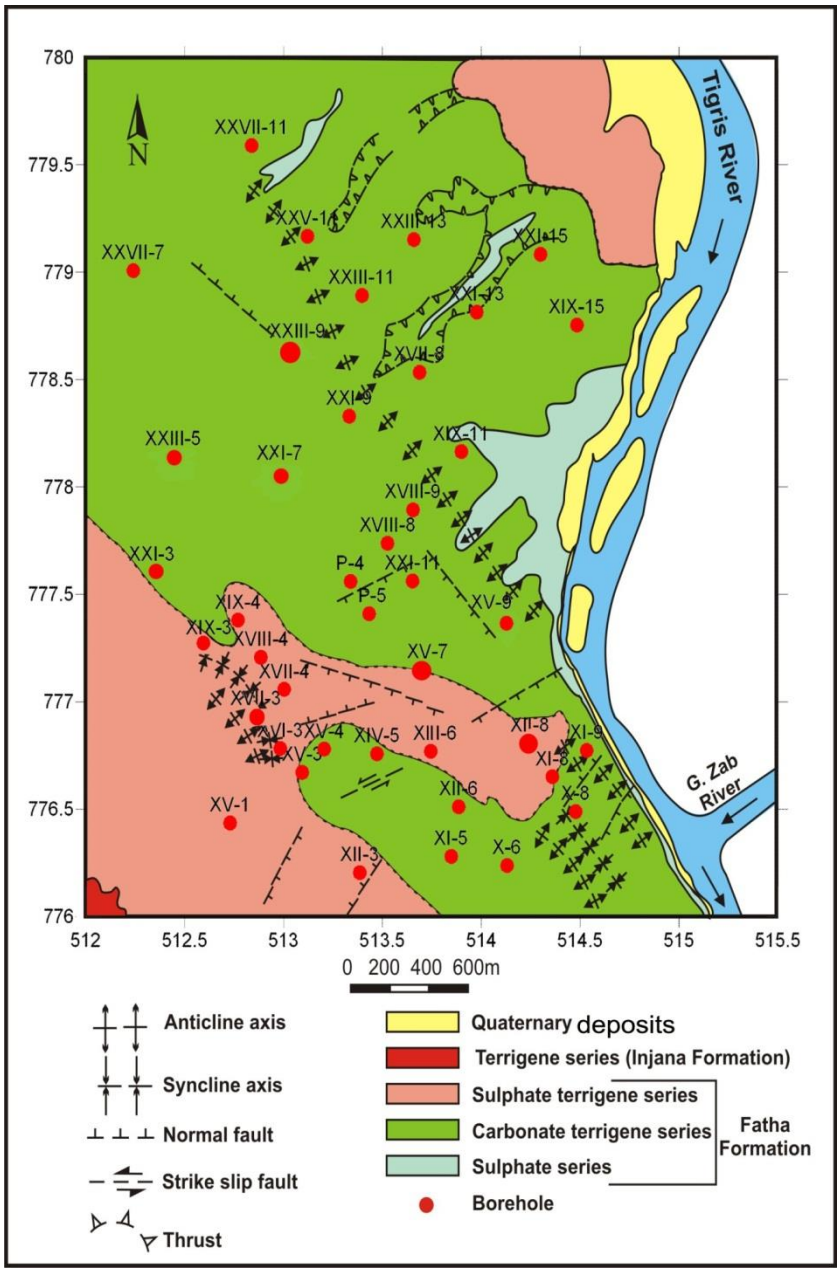

Fig. 1: Geological map of the study area [15]

Evaluation and Analysis Methods

After studying the geological data for nine wells drilled in the study area in 1970 AD by the Polish company Centrozap, they were obtained from the General Company for Mishraq Sulfur and on this basis, a mine assessment, calculation and estimation of mineral reserves of sulfur deposits were carried out using the program of Rockwork-14 with updated geological and mineral data show the following:

1- After studying the stratigraphic sequence of the formation of the hole over a wide area, starting from the Euphrates formation, whose depth varies according to the structural situation in the area, down to the surface of the earth, where it is revealed in most of the study area.

2- Sulfur deposits are concentrated in three beds of porous limestone to form the opening, separated by several heterogeneous layers of marley clay and dolomite limestone with different thicknesses, as shown in the figure (2).

3- All beds above the artificial layer (Horizon-1 first band), with different facies, were considered to be overburden.

4- All the beds separating the mineral layers or zones (the first, the second and the third zones) were considered insulating bed and were called the Waste beds Because it is not important in mining operations, it was considered a single insulating bed, regardless of its constituent rock facies, separating the mineralized sulfur beds, as shown in the aforementioned figures.

5- It was noticed by drawing the cross-section of the mineralized beds in the study area east-west and north-west-southeast, that there is an increase in

mineralization appearing in the core of the fold, in addition, it was noted that the least thickness of the overburden rocky cover is found above the top of the Mishraq anticline, especially at wells X-6 The XII-6 and XIII-6 figure (3).

6- The stripping ratio was calculated for the entire study area, which represents the ratio of the volume of the rock cover to the volume of the first mineralized bed Horizon-1, and it was equal to (6), while the maximum permissible percentage is (5), Table (1).

The stripping ratio is defined as the ratio between the volume of materials extracted from the sterile rocks to the volume of the raw materials extracted, and this ratio increases with increasing depth until it reaches a certain limit at which the mining works must be transformed into subsurface works [15]

Stripping ratio = Volume of Waste Rock Removed / Volume of Mineral Removed

7- The geostatistical method was adopted and used in calculating and estimating the reserve, as it is one of the applications adopted in the Rockwork-14 program, using which the area of expansion of mineral deposits is expanded depending on the base of applying the rule of the extent of the local impact of the models. In this method, a statistical treatment is carried out for the nine wells used in the calculation of the reserve and estimating the extent of their impact to farther distances from the sites of these wells after conducting statistical treatments in which the effect of the thicknesses of the mineralized beds is included and using the triangles method in which the average thickness of each triangle is estimated and the extent of its impact on the extent of the study area Figure (4) in which the thicknesses of the beds were relied From Table (2).

8- The calculations of reserve estimation for the three industrial layers (Horizon-1), (Horizon-2) and (Horizon-3) were carried out separately as in Tables (3), In which the distances of the impact range used in the statistical treatments up to the extension of the study area borders and the mineral reserve estimate according to the American classification, where the estimate is from the inferred reserve category, which depends on the geological characteristics of sulfur minerals, as well as the presence of a few wells obtained for the study area, which numbered (9) Wells where the degree of accuracy and reliability is low compared to the weighted reserve class in the American system, where the standard deviation rate ranged between (4.8 - 10.3), which are values that are considered acceptable in relation to the number of wells included in the study.

9- Calculations and estimation of the mineral reserve of sulfur as shown in Table (3), where the local density of ore was adopted and equal to (2.3 tons / m^3)[5], The total reserve of sulfur ore was equal to (484,922,218.6) tons of ore and after multiplying these Quantity at the rate of sulfur concentration in the ore, which is equal to 25%. The total rate of elemental sulfur was equal to (121,230,554,6) tons.

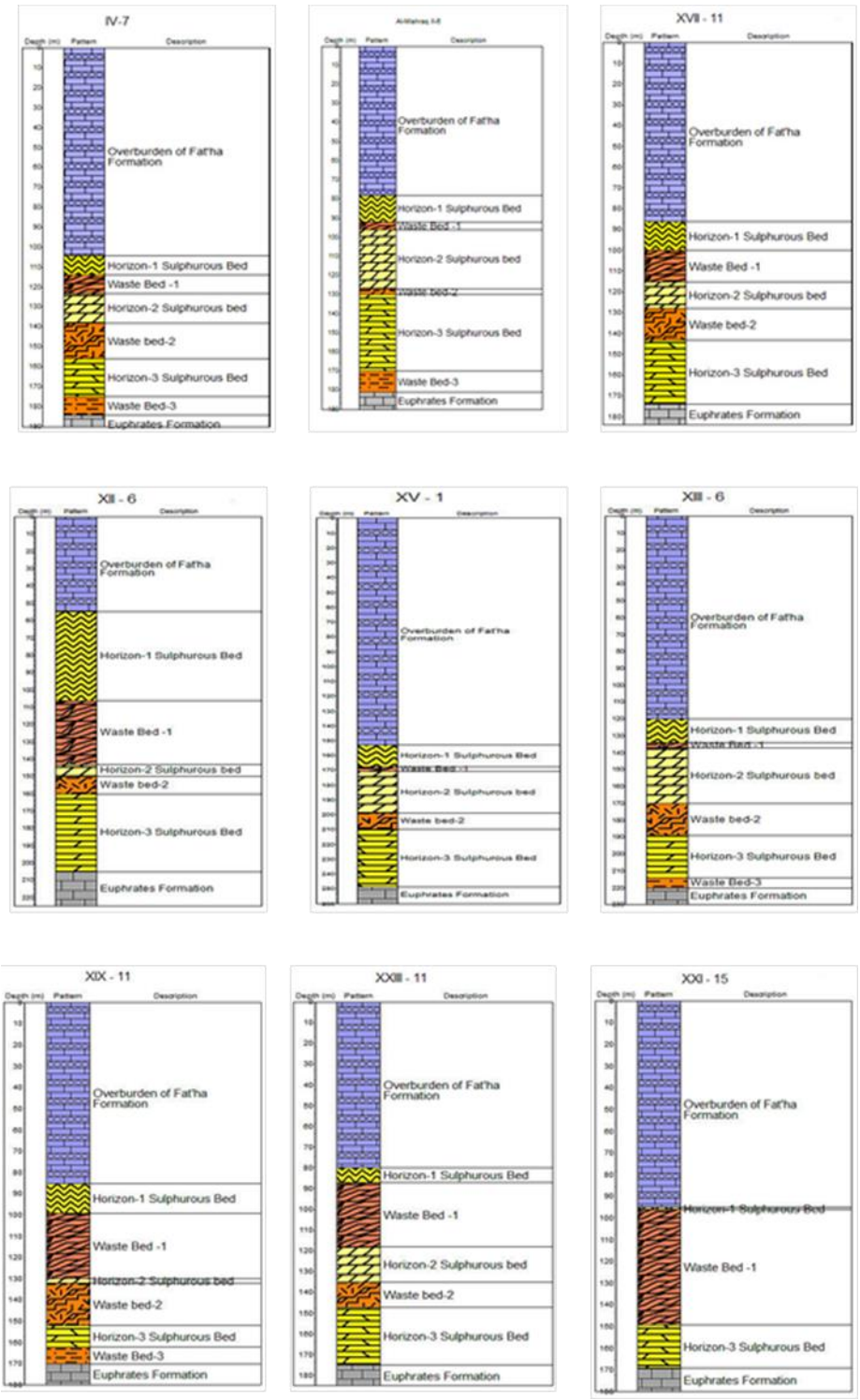

Fig. 2: Sulfur deposits and separating beds

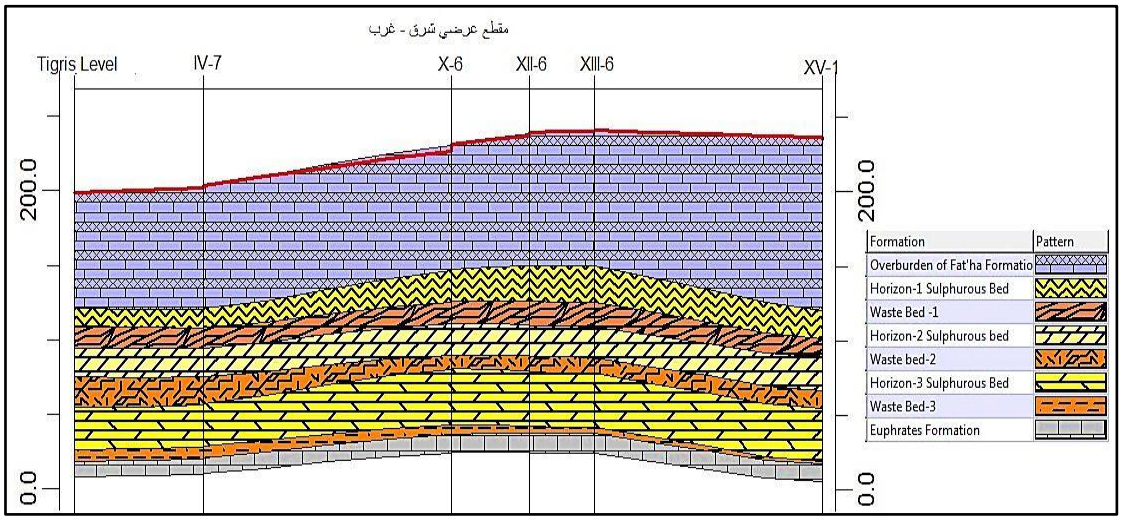

Fig. 3: East-West cross-section of the mineralized beds in the study area

Table 1: Calculation of Stripping ratio

Stripping ratio Calculation
Overburden of Mishraq – 1
Volumetric Report :
Total Points Used For Calculation ... 12
Points Removed By Filter ……. 0
Minimum Thickness Value ……... 55.0
Maximum Thickness Value ……... 153.0
Volume (cubic units) ……... 505,788,355.929
Weight (volume * density units) ..... 1,163 , 313 , 218.638
Volumetric calculations performed by Delaunay Triangulation method . Weight calculated by multiplying volume by density (2.3).
Distance - Qualified Reserves
Proven Reserves 0.0 Tons (0.0 Cubic METERS)
Probable Reserves 0.0 Tons (0.0 Cubic METERS)
Inferred Reserves 84,188,268.27 Tons (36,603,594.9 cubic METERS) ORE RESERVE
Unclassified 91 , 548,656.28 Tons (39,803,763.6 Cubic METERS) ORE RESERVE
Volumetric calculations performed by Delaunay Triangulation method . weight calculated by multiplying volume by density factor (2.3 ton / m3).
Average Percent of sulphur as Element = 25 %
Average Reserve of sulphur Elements = 21,047,067.06 Tons sulphur
Stripping Ratio = Volume of Overburden / Volume of Horizon – 1
= 505,788,355 / 84,188,268
= 6.0

Table 2: thicknesses of beds in the study area

Thickness of Sulphurous Beds in Mishraq-1											
B.H.No.	Easting	Northing	Total Depth (m)	Thickness of Overburden (m)	Thickness of Horizon-1 (m)	Thickness of Waste Bed 1 (m)	Thickness of Horizon-2 (m)	Thickness of Waste bed 2 (m)	Thickness of Horizon-3 (m)	Thickness of Waste Bed 3 (m)	Thickness of Euphrates Fn.(m) .
XIX-11	349167	3986059	180	85	14	31	2	20	10	8	10
XV-1	348014	3984320	260	153	15	3	28	11	39	0	11
XII-6	349169	3984406	225	55	51	37	7	10	45	0	20
XIII-6	349047	3984664	230	120	14	3	33	19	25	6	10
XXIII-11	348657	3987055	185	80	7	31	17	12	28	0	10
IV-7	350300	3983338	194	104	10	9	15	18	19	9	10
X-6	349415	3984135	190	78	14	4	31	2	41	11	9
XVII-11	349392	3985786	184	86	14	15	13	15	31	0	10
XXI-15	349558	3986981	180	95	1	53	0	0	20	0	11

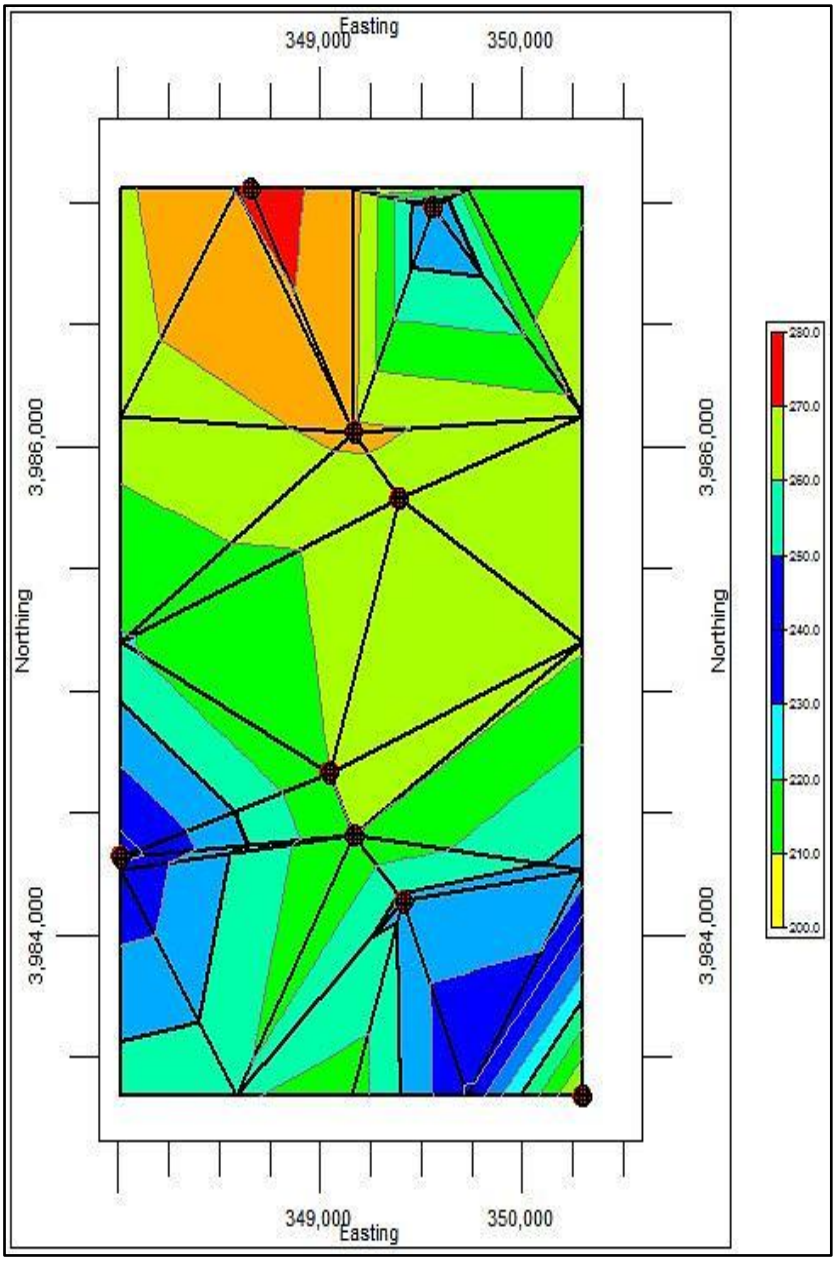

Fig. 4: Map of the reserve account area using the Kriging method

Table 3: Calculation and Estimation of Crude Reserves and Elemental Sulfur in the Study Area

Calculation and Estimation of Melting and Elemental Sulfur Reserves in Al-Mishraq Field-1
Horizon -1
Sulphurus Bed
Inferred Reserves ... 84,188,268.27 Tons (36,603,594.9 Cubic Meters) ORE RESERVE
Unclassified ..... 91,548,656.28 Tons (39,803,763.6 Cubic Meters) ORE RESERVE
Volumetric calculations performed by Delaunay Triangulation method.
Weight calculated by multiplying volume by density factor (2.3 ton/m3).
Average Percent of sulphur as Element= 25%
Average Reserve of sulphur Elements = 21,047,067.06 Tons sulphur
Horizon -2
Sulphurus Bed
Inferred Reserves ... 70,332,531.68 Tons (30,579,361.6 Cubic METERS) ORE RESERVE
Unclassified ..... 113,647,529.62 Tons (49,411,969.4 Cubic METERS) ORE RESERVE
Volumetric calculations performed by Delaunay Triangulation method.
Weight calculated by multiplying volume by density factor (2.3 ton/m3).
Average Percent of sulphur as Element= 25%
Average Reserve of sulphur Elements = 17,583,132.92 Tons sulphur
Horizon -3
Sulphurus Bed
Inferred Reserves ... 330,401,418.84 Tons (143,652,790.8 Cubic METERS) ORE RESERVE
Unclassified ..... 444,730,932.73 Tons (193,361,275.1 Cubic METERS) ORE RESERVE
Volumetric calculations performed by Delaunay Triangulation method.
Weight calculated by multiplying volume by density factor (2.3 ton/m3).
Average Percent of sulphur as Element= 25%
Average Reserve of sulphur Elements = 82,600,354.71 Tons sulphur
Total Reserve Estimation of Sulphurous Horizon
Inferred Reserves ... 484,922,218.68 Tons (210835747.25) Cubic Meters) ORE RESERVE
Volumetric calculations performed by Delaunay Triangulation method.
Weight calculated by multiplying volume by density factor (2.3 ton/m3).
Average Percent of sulphur as Element= 25%
Average Reserve of sulphur Elements = 121,230,554.68 Tons sulphur

Conclusions

Based on the study of the stratigraphic sequence and sulfur-containing layers of the available wells, the evaluation of the mining conditions, the estimation of crude sulfur reserves, and the discussion of the appropriate economically feasible extractive method in the study area, the following results were reached**:**

1- Sulfur mineralizations are concentrated in the core of the two-sided convex and submerged Mishraq fold.

2- The minimum thickness of the Overburden is found above the crest of the Meshraq fold, especially at wells X-6, XII-6 and XIII-6.

3- The reserve was calculated and estimated using the Rockwork-14 program, and the total reserve of crude sulfur in the study area in (Al-Mishraq-1) = 484,922,218,6 tons.

4- The total reserve of elemental sulfur was only (121,230,554,6) tons.

5- The stripping ratio, which determines the appropriate mining method for extraction, whether surface or subsurface, was calculated, and its value was equal to 6 in the entire study area.

6- The economic infeasibility of surface methods (open mine method) due to the value of the stripping ratio exceeding the maximum permissible limit in the study area, which is (5), in addition to environmental and geological problems that impede this method.

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التقييم المنجمي لترسبات الكبريت في منطقة المشراق باستخدام الطريقة الجيو احصائية

مزهر جار حسن الجبوري, غازي عطية زراك

قسم علوم الأرض التطبيقية, كلية العلوم, جامعة تكريت, تكريت, العراق

المخلص

تقع منطقة الدراسة في شمال العراق في الجهة الغربية المقابلة لالتقاء نهر دجلة مع رافد الزاب الأعلى على بعد حوالي 45 كم جنوب شرق مدينة الموصل ضمن نطاق حمرين–مكحول العائد لنطاق أقدام التلال ضمن المنطقة غير المستقرة. تحتوي المنطقة على صخور لتكاوين عديدة تتراوح أعمارها بين المايوسين الأسفل والعصر الرباعي وتضم تكاوين الفرات والفتحة والترسبات النهرية الحديثة. تتواجد ترسبات الكبريت في تكوين الفتحة ضمن الطبقة الانتاجية التي تحتوي على ثلاثة آفاق أو أنطقة رئيسية حاملة للكبريت تفصل بينها عدة طبقات غير متجانسة من الحجر الطيني المارلي والحجر الجيري الدولومايتي وبسماكات مختلفة. تكوّن الكبريت بسبب عمليات اختزال الجبس أو الأنهيدرايت بتوفر المواد الهيدروكاربونية وفعل البكتريا اللاهوائية حيث ينتج غاز كبريتيد الهيدروجين H_2S الذي يتأكسد فيما بعد عن طريق المياه الجوفية مكونا خام الكبريت بمساعدة عوامل أخرى تتمثل بالعوامل التكتونية والهيدروجيولوجية.

تم إعادة حساب وتقدير الاحتياطي المعدني لترسبات الكبريت باستخدام الطريقة الجيواحصائية كونها إحدى التطبيقات الحديثة المعتمدة في برنامج Rockwork-14 التي تأخذ بنظر الاعتبار موقع كل نموذج بالنسبة للآخر ضمن امتدادات الترسبات المعدنية وحتى خارج حدود تلك الامتدادات مما يعطي دقة وموثوقية عالية عن كمية الاحتياطي اعتمادا على مجموعة من المعايير المهمة مثل السمك ودرجة التركيز للخام والكثافة حيث تم تقدير الاحتياطي لعنصر الكبريت في حقل كبريت المشراق–1 بحوالي 121,230,554,68 طن.

تم مناقشة مدى صلاحية وملائمة استخدام طريقة المنجم المفتوح لاستخراج الكبريت في منطقة الدراسة استنادا إلى عامل حاسم ومهم هو نسبة القشط Stripping Ratio الذي يحدد نوع الطريقة الاستخراجية الملائمة وكان يساوي 6 لكامل منطقة الدراسة وهي قيمة كبيرة تجاوزت الحد الأقصى المسموح به وهو 5 وبذلك يتضح عدم ملائمة هذا الطريقة كونها غير مجدية اقتصاديا بسبب التكلفة الاستخراجية العالية ووجود الكبريت على أعماق مختلفة تتراوح بين 80–230 فضلا عن وجود مشاكل بيئية وجيولوجية تقف عائقا أمام استخدام هذا الطريقة في استخراج الكبريت.

استندت الدراسة على البيانات التي تم الحصول عليها لمجموعة من الآبار الاستكشافية التي حفرت في المنطقة والبالغ عددها (9).