Environmental impacts of the gypsum mining operation at Maqna area, Tabuk, Saudi Arabia

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Abstract The impacts of quarrying of the gypsum deposits on the environment at Maqna, Tabuk, were evaluated by intensive field studies including in situ testing, mapping and sampling of gypsum and well water. Field and laboratory tests were made to determine the engineering properties including tensile and compressive strengths, unit weight, fracture spacing and the rock quality designation (RQD) values. Results were used to determine the most suitable method for quarrying and extraction. Chemical analyses of gypsum and water well samples were conducted along with mineralogical analysis using X-ray diffraction analysis (XRD). Results show that there are no harmful impacts on the environment of the studied area associated with the extraction and quarrying of the gypsum deposits at the Maqna area. They also revealed that the gypsum can be quarried using a ripping technique, which does not create noise and/or vibration in the surrounding areas.

Keywords Gypsum · Anhydrite · Cement · Quarrying · Pollution and environmental geology · Saudi Arabia

Introduction

General

The quarrying and mining of ore deposits and the transportation of these products to the market now represent one of the most important environmental problems that cause air and water pollution. They may also cause pollution from the noise and vibration that commonly accompany them. If scientific and good preventative methods are used they can prevent adverse affects on human health and avoid disturbance of the ecosystem. The Kingdom of Saudi Arabia government has issued regulations for developing projects that require detailed scientific and environmental studies in order to retain a healthy environment.

Gypsum is considered to be one of the most economical ore deposits that can be used in construction work. It is commonly used as an additive material in the manufacturing of cement and glass and in improving soil. It is also used as a decorating material and in the preparation of concrete and bricks. During the manufacture of cement, about 3–6% of gypsum raw material or anhydrite is added to the mixture because it allows finer grinding of the materials. Gypsum is used essentially as "Plaster of Paris" after heating to 180 °C, where it losses about 75% of its water content and its chemical composition changes from $CaSO_4\ 2H_2O$ to $CaSO_4\ H_2O$.

The largest known source of gypsum in the Kingdom occurs as small deposits along the coastal plain of the Red Sea between the Gulf of Aqaba and Yanbu Al Bahr (Fig. 1). The Maqna area contains a reserve of up to 33.6 Mt with gypsum content in the deposits ranging from 85 to 90% (Lurant and others 1989; Deputy Ministry for Petroleum and Mineral Resources 1993; Sahal and Al Shanti 1999). There are four zones of gypsum deposits available for industrial use. Three of these zones are in the Maqna area (Jabal Al Raghama and the surroundings) and the fourth is on the coast near Maqna town. At Jabal Al Raghama, the first zone contains 13 Mt with average gypsum content of about 83.6%. The gypsum content may reach up to 90% in the top 8 m. The second zone contains approximately 3.6 Mt with a gypsum content of about 90% within a thickness of 10–17 m. The third zone is 8 m thick and contains 9 Mt with an average gypsum content of about 90.5%. The fourth zone is about 10 m thick and contains 8 Mt with an average gypsum content of 86%. These geological reserve values were measured using the drilling data performed by the Deputy Ministry for Petroleum and Mineral Resources (1993). The deposits are most extensive in the Bad' formation, which attains a maximum thickness of about 150 m at Maqna and its surroundings (LeNindre 1981).

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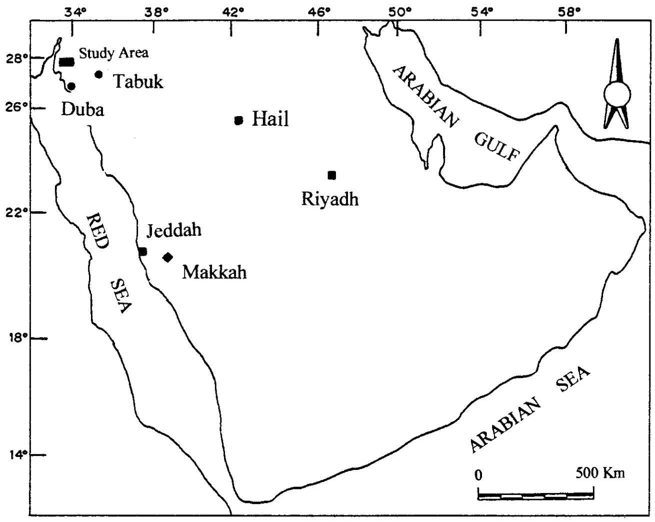

Fig. 1
Location map of the study area

Location

The Maqna area lies in the northwestern corner of the Kingdom of Saudi Arabia. It is about 28 km east of Maqna City and about 123 km north of Duba City in the Tabuk Region. The area lies between longitudes 34°40′ and 35°00′E and latitudes 28°10′ and 28°30′N (Fig. 1).

Purpose

The main purpose of this study is to assess and evaluate the environmental impacts of quarrying and exploitation of gypsum deposits at the Maqna area, Tabuk, Saudi Arabia, including the effect of quarrying of gypsum on air pollution, the vibration and noise during extraction of the ore deposits, and the impacts on the topography and natural landscaping of the area, on the surface and underground water and on the natural vegetation, human health and safety of animal and plant life. The most suitable quarrying process and the optimum method for safety during the transportation of ore from the quarry to the market were determined. The study was considered to be necessary before quarrying of the gypsum deposits at the Maqna area due to the environmental sensitivity of the location.

Social and economic aspects

The Tabuk Region is one of the least populated in the Kingdom of Saudi Arabia. It has about 2.9% of the population of the Kingdom (of which 1.57% are in Tabuk City, 0.93% in Duba and Al Wagh cities, and 0.4% in the other villages of the region; General Statistical Authority 1993, 1997). Figure 2 shows the distribution of population density for the Kingdom (Al Shawaf and Zahed 1988). The population of the study area is low and concentrated mainly in the Al Bad'a, Maqna and Ash Sharaf towns and in several other villages. A small semi-nomadic Bedouin population rears sheep and goats. The study area is generally unpopulated (Al Rawessi 1978; Salma 1996).

Geology and geomorphology

Geology of the Maqna area

The investigated area lies in the western corner of the Kingdom of Saudi Arabia, east of Maqna on an extension

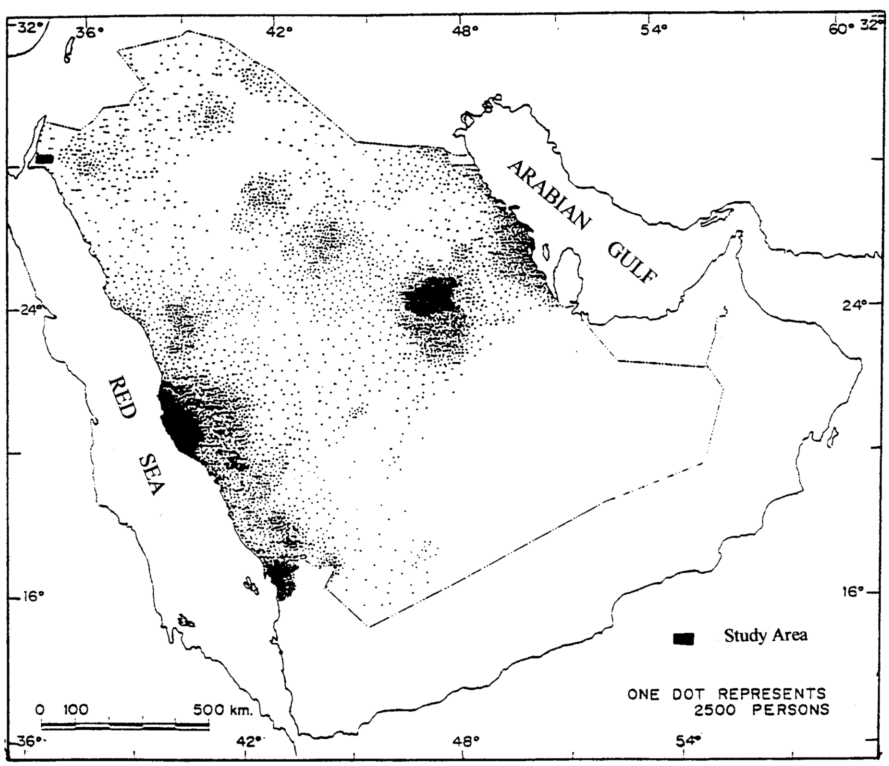

Fig. 2
An index map showing the distribution of the population in Saudi Arabia

Fig. 3
Photograph showing a general view of the Maqna gypsum deposit

parallel to the Gulf of Aqaba coast. The crystalline igneous basement rocks, namely granite, quartz syenite, quartz diorite, diorite and granodiorite, occupy the northern, northeastern, eastern and southeastern parts of the studied area. Many dykes of rhyolite and andesite of Precambrian age invade these rocks. In the southwestern part of the studied area, there are sandstone and conglomerate of Tertiary age. In the west, a window of granodiorite exists and is surrounded by sandstone and conglomerate rocks of Tertiary age as well as recent sediments. In the southern part of the studied area, Tertiary and recent sediments of gypsum cover the majority of the area.

Gypsum deposits at Maqna cover an area of about 200 km^2, forming elongated hills of moderate height (200–500 m) that slope steeply towards the coast of Gulf of Aqaba (Fig. 3). These deposits represent an evaporated mass and the area has wadis eroded to depth to exposed older beds and a plunging anticline towards the south with an axis trending northeast. The average thickness of gypsum attains about 130 m. Most of the evaporites are well developed in the northeastern (lower middle Miocene) and southern parts of the area (upper middle Miocene and upper Miocene) (Fig. 4).

The Al Raghama group overlies the crystalline basement rocks in the north and east. In the south and west it is underlain by sandstone and conglomerate of Tertiary age. The rocks of Al Raghama group are subdivided into three rock units:

- Lower unit: limestone, dolomite and fossiliferous limestone, layers of sandstone, conglomerate and marl. All are overlain by lenses of gypsum.
- Middle unit: marl and layers of gypsum alternating with each other and with clay and limestone.
- Upper unit: thick evaporites (gypsum and anhydrite) alternating with marl, dolomite sandstone and conglomerate. All are overlain by a bed of black dolomite.

Gypsum and anhydrite deposits occur within the Al Raghama group as lenses in the lower unit, three beds in the middle unit and large thick bodies in the upper unit. The gypsum reaches its maximum thickness towards the south and northeast (exceeding 130 m) and then the beds gradually become thinner until they disappear towards the north in the Bada area.

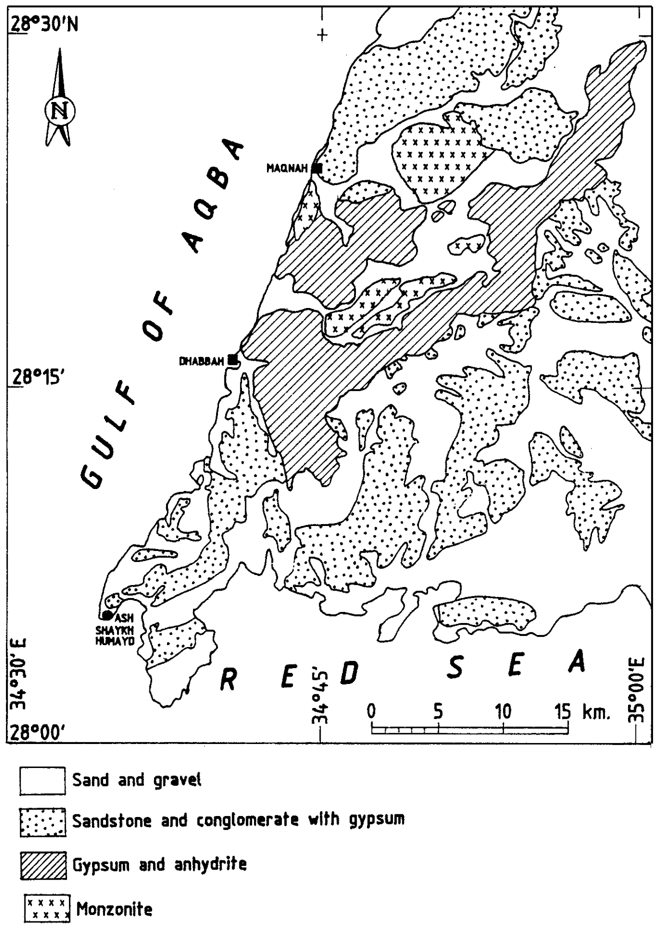

Fig. 4
Geologic map of the study area

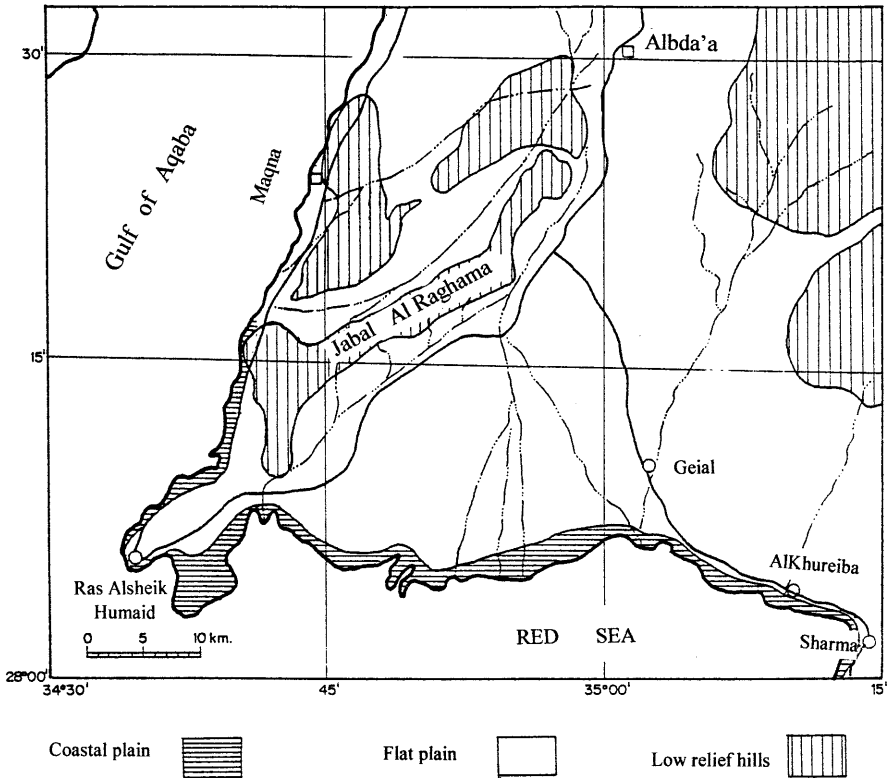

Fig. 5
Topographic map of the study area

It seems that most of the evaporite masses consist of anhydrite with surfacial gypsum probably resulting from rehydration of the original anhydrite at a depth of 15–20 m below the surface. Both the surface and shallow drilling samples show the presence of gypsum/anhydrite of high purity and contain less than 0.05% silicon dioxide and traces of aluminium oxide, iron oxide, sodium oxide and magnesium oxide as well as chlorine (Lurant and others 1989).

Geomorphology of the Maqna area

The area comprises a series of moderately high, rugged mountain ridges ranging from 150 to 500 m above sea level (Fig. 5). The mountain chain of Jabal Al Raghama lies in the middle part, while the Hamda Mountains lie to the north of it. Mandasa and Al Natish Mountains lie in the northwestern part and are close to the coast and lower. The Richa and Kabrit Mountains are in the western part of the area parallel to the coast. The average height of these hills reaches about 180 m above sea level and lie in the eastern part of Jabal Marw and Jabal Rahm.

The other parts of the area are mostly represented by a peneplain intersected by a number of small wadis draining west towards the Gulf of Aqaba or southwest towards the Red Sea. The height of this peneplain decreases gradually towards the coast (Al Welaie 1996). The area is classified into three main topographic parts (Al Sherief 1994; Bandakage 1994; Fig. 5): low relief hills, plains of flat wadis and coastal plains.

The Jabal Al Raghama area comprises many hills of low elevation (50 to 100 m above the ground surface), which extend NE–SW and are underlain by beds dipping towards the southeast. Locally, the hills appear as irregular surface domes due to variation in the surface weathering and erosion. Little vegetation is present in the chain of hills that constitutes Al Raghama Mountain (Fig. 6), because of the chemical composition of the rocks, which prevents the growth of vegetation in the dry areas.

Results

Chemistry and mineralogy of Maqna gypsum deposits

Gypsum and anhydrite are considered as sulfate minerals of a chemically deposited sedimentary rock. The theoretical chemical composition of gypsum is 32% Ca O, 46% SO_2 and 21% H_2O. Anhydrite consists of 40% CaO and 60% SO_2. Unlike anhydrite, gypsum contains water in the crystal structure, where 15% H_2O has a weak bonding and 6% is strongly bonded in the crystal lattice structure. The hardness of gypsum is about 2 and therefore it is easily ground into fine powder, while anhydrite has hardness which ranges from 3 to 3.5.

The specific gravity of gypsum is less than 2.4, as compared to 2.9 for anhydrite. Gypsum and anhydrite occur in granular form (massive or crystalline) or as fibrous mass, often with a white to grey colour (due to impurities). The different types of gypsum include selenite, alabaster (fine grained and used by artists because it is easily cut), satinspar (fibrous and filled with cracks) and gibbsite (mixture of gypsum, calcite and sands) (Deputy Ministry for Petroleum and Mineral Resources 1993).

Fig. 6
Photograph showing the low relief hills of gypsum deposit in the study area

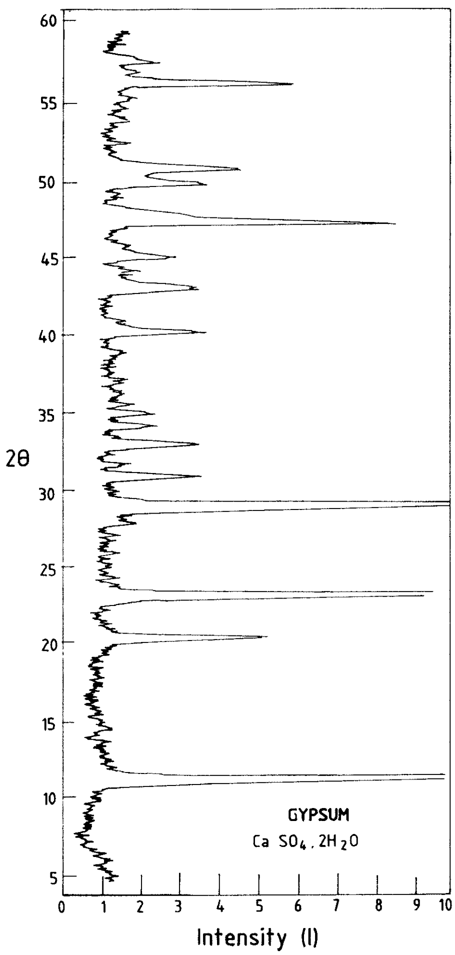

Fig. 7
A chart showing the results of XRD analysis of Maqna gypsum

The results of mineralogical study and X-ray diffraction (XRD) analysis confirm the presence of gypsum deposits with gypsum content over 90% and a small amount of anhydrite. It was found that the gypsum at the Maqna area has a high degree of purity and physical characteristics which promote its use in cement manufacturing. The results of XRD analysis revealed the purity of gypsum deposits (Fig. 7), with the presence of minor contents of anhydrite in some analysed samples (Fig. 8).

Chemical analyses from 70 samples at 20 locations of the gypsum deposits were undertaken to determine their major and minor element contents and the existence and amount of harmful elements. These include Pb, Cu, Zn, Hg, Li and Cd, which are harmful to the health. Table 1 shows the average content of major and minor elements in gypsum at the Maqna area. There are no radioactive elements (Th and U) or high contents of harmful elements in these gypsum and anhydrite deposits.

No major health problems are expected to be associated with the quarrying of gypsum (Environment Canada 1996). The workers in quarries must take necessary precautions, particularly when the dust content in the air of the area exceeds 10 g/m^3 (Shanahan 1994).

Climatic factors

General

The temperature, rainfall and relative humidity are considered to be the most important climatic factors that may affect the environment. The influence of these factors appears in the type and purity of surface and underground water as well as the fungal, vegetarian and pastoral life in the area. The effects of wind velocity and directions are clearly noticed in the pollution of air during the process of quarrying and transportation to the factory.

The region in which the Maqna area is situated has a continental desert climate which varies locally with to proximity to the Red Sea. It receives localized rainfall, mainly during the winter. Because of the high topographic relief in the area, major extremes in temperature are found. The lowest areas commonly have temperatures of 45 °C in summer, whereas in the mountainous areas and

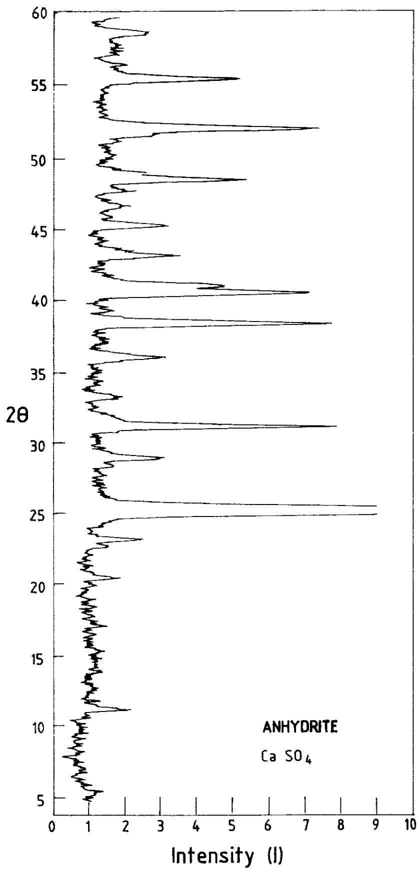

Fig. 8
A chart showing the results of XRD analysis of Maqna anhydrite

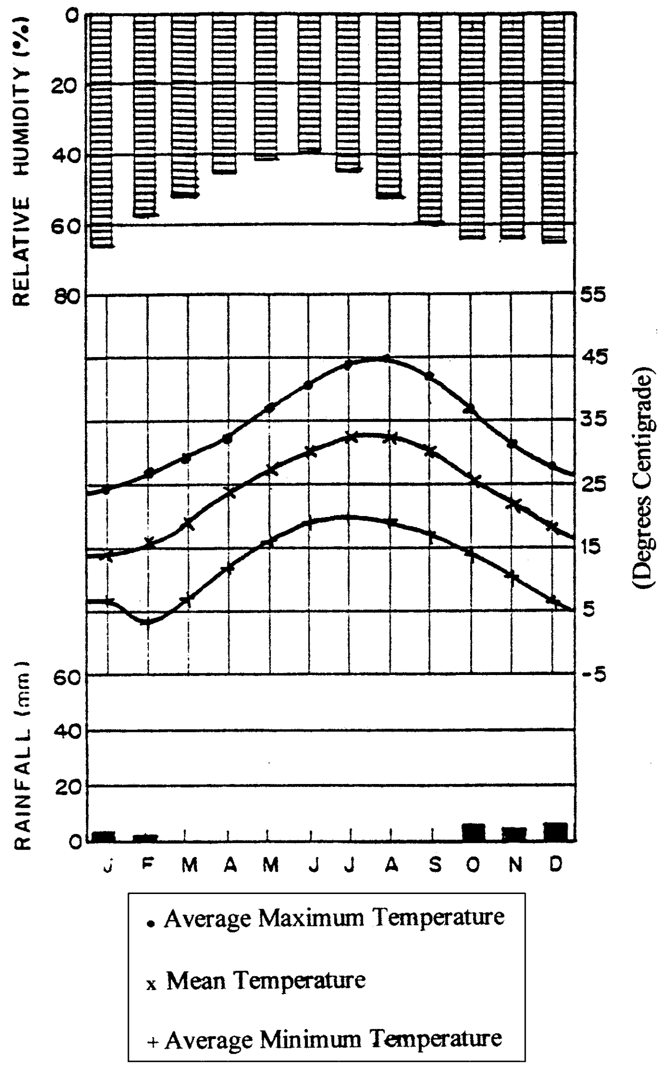

Fig. 9
A chart showing a summary of the temperature, rainfall and relative humidity in the study area

Table 1
Results of chemical analyses of major, minor and harmful elements of Maqna gypsum deposits. The harmful elements represent ppm of 1.99% residue for gypsum and of 1.62% residue for anhydrite

	Gypsum deposits	Anhydrite deposits
Major elements		
Sulfur dioxide (%)	43.86	53.05
Calcium oxide (%)	33.07	39.34
Water (%)	13.56	2.88
Minor elements		
Lost crystalline water (%)	6.74	2.45
Magnesium oxide (%)	0.40	0.12
Sodium oxide (%)	0.15	0.22
Silicon dioxide (%)	0.12	0.22
Potassium oxide (%)	0.05	0.06
Iron oxide (%)	0.04	0.02
Aluminium oxide (%)	0.02	0.02
Total elements	98.01	98.38
Harmful elements		
Strontium (ppm)	85.00	112
Zinc (ppm)	63.34	84
Barium (ppm)	48.67	52
Vanadium (ppm)	48.33	39
Lithium (ppm)	18.33	25
Copper (ppm)	13.33	6
Lead (ppm)	7.34	11
Cadmium (ppm)	0.01	0.01
Mercury (ppm)	0.00	0.00

on the Haqabat Hisma winter temperatures at night may fall below freezing. Snow fell on the mountains during the 1982 and 1983 winter seasons. In winter, strong north-westerly winds may cause severe sandstorms, especially over the coastal plain. Apart from date palms, ushr trees, rushes and grasses near springs, and clusters of dom palms along the coast, natural vegetation is restricted to sparse bushes and thorny trees and to plants along wadi beds. The area of Maqna lies close to the Red Sea coast and is dominated by very hot weather in summer and moderately cold weather in winter. It is also characterized by a high rate of relative humidity in the summer season. Rain falls in winter in some years but generally rainfall is rare (Ministry of Agricultural and Water 1985–1999). The rate and average values of temperature, rainfall and relative humidity are summarized in Fig. 9 and Table 2.

Temperature

The variations of maximum, minimum and mean temperature in the Maqna area and surrounding areas during

Table 2
Summary of the rate and average values of temperature, rainfall and relative humidity in the study area according to the seasons of the year

Season of the year (months)	Rate and (average) of temperature (°C)	Rate and (average) of rainfall (mm)	Rate and (average) of relative humidity (%)
Winter (December–January–February)	10–16 (14)	10–20 (12)	55–65 (60)
Spring (March–April–May)	22–26 (24)	0–10 (5)	40–50 (45)
Summer (June–July–August)	30–38 (34)	0–5 (1)	40–55 (50)
Autumn (September–October–November)	22–28 (26)	0–5 (2)	60–65 (60)

the months of the year are given in Fig. 9. The range and average values of temperature, rainfall and humidity in the area have been summarized for the different seasons of the year (Table 2). The high temperature may cause gypsum to lose some of its water and/or humidity. This may cause some slight changes in the chemical composition of gypsum and thus partially change it to anhydrite.

Precipitation

The annual rainfall is 15 to about 20 mm/year (Fig. 9 and Table 2). However, this is considered to be a very low rate to supply wells and growing fungi plants in the study area. It is noticed that the average amount of rain in the winter season is about 12 mm and that winter is the season with the highest rate in the area . Generally, rainfall in the area is irregular (Ministry of Agricultural and Water 1985–1999).

Relative humidity

The relative humidity in the area ranges between 45 and 60% (Fig. 9 and Table 2). However, the relative humidity is affected by the variation of both weather and natural topography of each area. The high humidity influences human activity, especially in the summer season. The humidity may be considered as an important factor controlling the nature of evaporites (the relative abundance of gypsum to anhydrite in the area).

Wind directions

The direction of the wind is generally north to northwest (Fig. 10). The velocity of the wind is about 10 to 40 km/h. However, the velocity and directions differ in the different seasons of the year (Ministry of Agricultural and Water 1985–1999). Therefore, air pollution in the study area and surroundings due to the process of quarrying of Maqna gypsum will mainly have its effect in the south and southeast directions. Tabuk City is towards the southeast from Maqna, while a few villages and Duba and Al Wagh cities are in the southern direction. Precautions must be taken to prevent quarrying and freighting at the time of strong winds.

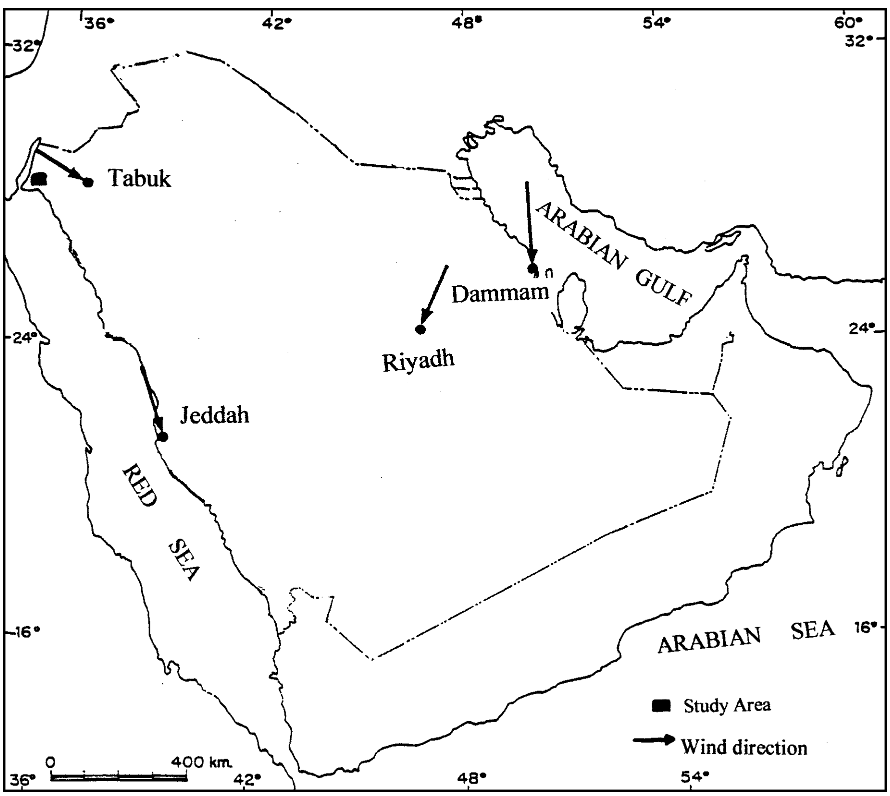

Fig. 10
An index map showing the predominant wind directions in Saudi Arabia and the study area

Table 3
Results of the chemical analysis of tested water samples from Maqna area with a comparison to the fresh water limits (after World Health Organization 1984)

	Tested water (ppm)	Fresh water (ppm)
Ions		
Chlorides	1,195.6	250–600
Sulfates	799.3	200–400
Bicarbonates	157.2	30–100
Nitrates	35.6	30–100
Fluorides	0.8	1–1.5
Content of solid substances	841.1	–
Cations		
Sodium	790.5	10–20
Potassium	3.5	10–20
Calcium	289.8	75–200
Magnesium	28.5	30–150
Iron	0	0.3–1
Content of solid substances and salts	3,392.0	1,000–1,500

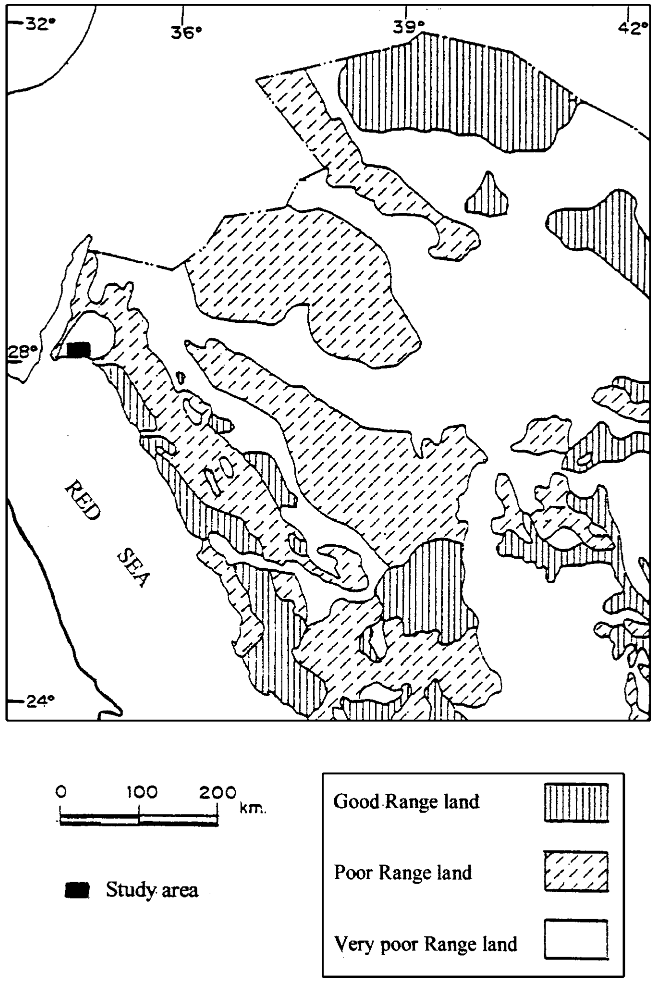

Fig. 11
An index map showing the distribution of the range land in the northern part of Saudi Arabia and the study area

Hydrology of the study area

The presence of groundwater at great depth and the scarcity of vegetation are attributed to a high evaporation rate of limited surface water due to high temperatures in the summer season. The depth of groundwater, at Maqna, close to Jabal Al Raghama, ranges from 70 to 90 m, and decreases until it reaches 10 to 15 m below ground surface close to the sea. At the Red Sea coast the depth to groundwater is only 1 to 2 m.

Water from wells in the study area has been chemically analysed (Table 3) and contains high concentration of soluble salts (3,392 ppm), chlorides (1,195 ppm), sulfates (799 ppm) and bicarbonates (157 ppm) as anions, and sodium (790 ppm), calcium (290 ppm) and magnesium (28 ppm) as cations. These values exceed the permissible limits for drinking water (World Health Organization 1984).

Life aspects in the study area

Animals resources

Generally, Tabuk area has the least animal resources in the Kingdom due to the relative scarcity of pastures (Ministry of Agricultural and Water 1998). Groups of a few camels, sheep and goats graze near the inhabitant groups, but not close to the quarry, and the impact of quarrying on animal health is negligible.

Natural pastures

The study area lies within poor to very poor range land as shown in Fig. 11 (Ministry of Agricultural and Water 1998). This is attributed to the low rainfall, which is insufficient for vegetation and inadequate for animal life. The Maqna area is nearly devoid of grass, trees and other plants.

Quarrying and transportation

Quarrying techniques

Quarrying methods and transportation to factories are prime factors that negatively affect the environment and must be controlled. The method of quarrying depends on two major engineering factors: (1) the strength of the rock and (2) the spacing between the joints, fractures or beds or the rock quality designation (RQD) values. The uniaxial and tensile strengths of Maqna gypsum and the RQD values have been measured using the point load and the uniaxial compressive strength according to the methods suggested by Brown (1981). These measurements were performed on more than 70 rock samples taken from 20 locations. The results are summarized in Table 4. It was found that the compressive strength of Maqna gypsum ranges from 20 to 31.5 MPa, while the tensile strength ranges between 1.05 and 1.31 MPa. For anhydrite samples, the uniaxial compressive strength ranges between 30 and 36 MPa, whereas the tensile strength ranges between 1.4 and 1.5 MPa. The average distance between the fractures in terms of joint spacing

Table 4
Results of some engineering properties of Maqna gypsum

Location no.	Specific gravity	Tensile strength (MPa)	Compressive strength (MPa)	RQD values (%)
1	1.9	1.10	26.40	13
2	1.9	1.05	20.26	10
3	2.1	1.31	31.44	39
4	2.0	1.15	27.37	21
5	2.0	1.25	25.00	21
6	1.9	1.13	24.86	18
7	1.9	1.2	24.00	16
8	1.9	1.18	24.19	18
9	2.0	1.28	29.44	32
10	1.9	1.21	29.04	30
11	2.0	1.30	29.25	31
12	1.9	1.14	26.22	16
13	1.9	1.19	27.14	15
14	2.1	1.29	29.97	24
15	1.9	1.10	21.18	13
16	1.9	1.07	24.08	15
17	2.87	1.52	36.08	40
18	2.6	1.46	32.02	38
19	2.7	1.50	34.05	38
20	2.4	1.43	29.93	20

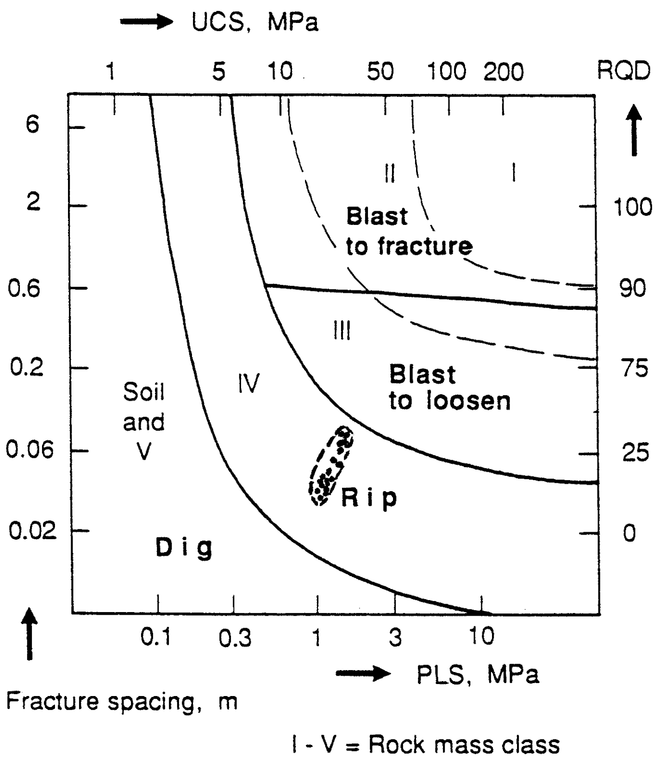

Fig. 12
Engineering classification for quarrying techniques for rocks and soils showing the most suitable method for Maqna gypsum. (Modified after Goodman 1989; Waltham 1994)

was found to be less than 20 cm, and the RQD values range between 10 and 40%.
The results of the field measurements and the laboratory tests are plotted in Fig. 12, which is modified after Goodman (1989) and Waltham (1994). The ripping technique would appear to be the most appropriate method for quarrying and extracting the gypsum deposits at Maqna quarries.

Vibrations and noises

Vibration and noises that commonly accompany the process of quarrying are potentially the most environmentally adverse factors that affect human or animal health. The effect of vibration and noises may cause pollution of air with dusts, harmful gases and noises. The problems of vibration and noises are usually associated with blasting techniques. In this study, the ripping quarrying technique is recommended (Fig. 12) and no environmental or health problems are expected to accompany it.

Transportation method

The distance between the quarrying and the closest cement factory, at Tabuk Cement Company, is about 123 km. The road passes by several towns and villages and care must be taken to cover the load trucks tightly to avoid air and environmental pollution.

Conclusions

The evaluation of the environmental impacts resulting from the quarrying process of gypsum from Maqna area is summarized in Table 5. It includes the effects of the process on the environment and the recommendations that should be considered. The method of quarrying and extracting of ore deposits as well as their transportation are considered the most important environmental problems that may cause air and water pollution in addition to the noises and vibration. The ripping technique is the most appropriate method for quarrying and extracting the gypsum deposits at Maqna quarries. The site of quarrying is uninhabited and there are no residential housing, industrial or agricultural activities present. The nearest community is about 20 km from the site.

Table 5
Summary of the environmental impacts due to the quarrying of gypsum at the Maqna area

Subject	Effects	Recommendations
The social/economic aspects		
Local economy of the area	Employs some citizens in the area	Offering more employment
Buildings	No effect	Absent
Roads	No effect	Absent
Effects on the air		
Air pollution	No effect	No quarrying and transportation during windstorms, and covering the trucks
Noises	No effect	Absent
Vibrations	No effect	Absent
Topography of the area		
Shape of the earth	Removing some hills	Absent
Natural view	No effect	Absent
The effect on life		
Animal life	No effect	Absent
Vegetation and agriculture	No effect	Absent
Pastoral life	No effect	Absent
Effect on hydrology		
Groundwater	No effect	Absent
Surface water	No effect	Absent
Health aspects		
Human health	No records of effects	Absent
Animal health	No records of effects	Absent
Safety required at site of quarrying		
During quarrying period	Not required	No need
After quarrying period	Not required	No need

It is necessary to take the precaution during transportation of gypsum deposits from the site of quarrying to the factory of covering the load of the trucks tightly to prevent air pollution along the road. Quarrying should stop during strong windstorms, and workers on the site of quarrying are required to use medical masks at the time of quarrying.

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