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Geological Complications and Environmental Hazards of the Cement Raw Materials Quarry Sites in Yemen

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ABSTRACT: Extensive field and site investigations were conducted to assess and evaluate the situation in quarries presently exploited for the production of cement raw materials in Yemen. These quarries have several geological complications represented mainly by high elevations, steep slopes, rugged topography, heterogeneity in bed thickness, lithologic composition and quality, presence of igneous sills and dykes, intensive fracturing and jointing, and abundance of karstification features. Moreover, the processes of quarrying and related activities have several negative environmental impacts, the most important of which are soil failure, overburden and land sliding, toppling and rock falls (which result in considerable mass wasting) as well as dust and noise emissions. Generally, quarrying operations are more hazardous in quarries of gypsum and basement rocks than in those of carbonates and volcanics. Furthermore, the quarries have problems related to the conservation of natural resources. These are represented primarily by the excavation of the valuable agricultural and reclaimed lands and improper exploitation of the cement raw materials, as well as the depletion of fresh and underground water reserves. To deal with the above-mentioned problems, a number of recommendations are outlined. They comprise mitigation measures which must be strictly implemented. Also, it is of utmost importance to conduct prospecting for new occurrences of cement raw materials and their possible substitutes as well as additional groundwater resources.

Keywords: Cement raw materials; Geohazards; Geological complications; Quarries; Yemen.

التعقيدات الجيولوجية والمخاطر البيئية لمواقع محاجر مواد خام الأسمنت في اليمن

أحمد محمد العنوة، محمد إبراهيم الأنبعاوي، محمد محمود أبو زيد وإبراهيم عبدالحميد الأكحلي

الملخص: تم اِجراء تحريَات حقلية وموقعية مُستفيضة لتقييم وضع المحاجر المُستغلة -حاليًا- لاستخراج مواد خام صناعة الاسمنت في اليمن. حيث توجد في هذه المَحاجر العديد من التَعقيدات الجيولوجية المُتَمَثِلَة بِشكلٍ أساسي في: الارتفاعات العالية، المُنحدرات الشديدة، التضاريس الوَعِرة، عَدم التجانُس في سُمك الطبقة، التكوين الصخري وجَودَتِه، وجود السُّدود والقَواطع النارية، الشُقوق والفواصل الكثيرة، وكثرة الظواهر الكَارستية. كما أنَّ لعمليات التَحجِير والأنشطة المُرتبطة بها تأثيرات بيئيّة سلبية متعددة؛ من أهمها: اِنهيار التربة، الغِطاء التُرابي، الانزلاقات الأرضية، اِنقلاب وتَساقط الصخور (مما يؤدي إلى هَدر كُتلي كَبير)، بالإضافة إلى اِنبعاثات الغُبار والضوضاء. عُمومًا، تعتبر عمليات التَحجير في مَحاجر الجبس وصخور القاعدة أكثر خُطورة مما هي عليه في صخور الكربونات والبركانيات. كما أنَّ للمحاجر مشاكل تتعلق بالحفاظِ على المَوارد الطبيعية؛ والمُتَمَثِلة بشكلٍ رئيسي في: حفر وتجريف تربة الأراضي الزراعية، والاستغلال غير الأمثل لمواد خام صناعة الاسمنت، فضلًا عن اِستنزاف مخزون المياه الجوفية. للتعاملِ مع المشاكل سَالفةِ الذِّكر، تمّ وضع عدة توصيات؛ تشمل تَدابير للتخفيف والحد من الاستغلال غير المناسب لمواد خام صناعة الاسمنت ويجب تنفيذها بدقة. كما يجب البحث عن مواقع جديدة بدلًا عن المواقع المستغلة -حاليًا- لاستخراج مواد خام صناعة الاسمنت وبدائلها الممكنة، بالإضافة إلى مصادر مياه جوفية اِضافية.

الكلمات المفتاحية: مواد خام الاسمنت، المخاطر الجيولوجية، التعقيدات الجيولوجية، المحاجر، اليمن.

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1. Introduction

The cement industry in Yemen is based on six main plants located in the western part (Amran, Bajel, Al-Barh) and southern (Abyan, Lahj and Al-Mukalla) parts of Yemen (Figure 1). These plants produce about six million tons/year of Portland Cement [1]. Additional production lines in these plants as well as new factories are under construction. The natural cement raw materials (carbonates, sand, clay, gypsum, correctives and additives) are available in the vicinities of these plants. Abu-Zeid *et al.* [2] reported that these raw materials exist in the Jurassic Amran Group (Shuqra, Madbi, Nayfa and Sab'atayn formations), the Cretaceous Tawilah sandstone, the Tertiary Trap Series, the Quaternary Yemen and Aden Volcanics and the Quaternary wadi deposits as well as some in the Precambrian Basement rocks (Table 1). The stratigraphy and tectonic setting of these rock units have been studied by several researchers [3-21].

Table 1. Lithology of the rock units comprising the cement raw materials [20].

Age	Rock unit	Lithology	Raw material	Sector A			Sector B		Sector C
				*Am	Bj	Br	Lh	Ab	Mk
Quaternary	Wadi Deposits	Gravel, sand, silt, clay, loess	Sand-clay	√	√	√	√	√	√
	Yemen Volcanic Series	Basic volcanic ash and lapilli, vitrophyric basalt, basaltic lava flows and volcanic cones.	Substitutes	√	√	√	–	√	√
Tertiary	Salif Evaporites	Rock salt, gypsum, gypsiferous clastics	Gypsum	–	√	–	–	–	–
	Yemen Trap Series	Olivine basalt, hawaiites, mugearites, peralkaline rhyolites pyroclastics, ignimbrites.	Substitutes	√	√	√	√	–	–
	Hadramawt Group	Limestone; mainly fine-grained, massive, weathered in places, nodular, often with calcite and chert veins	Carbonates	–	–	–	–	–	√
			Gypsum	–	–	–	–	–	√
Cretaceous	Tawilah Group	Sandstone; fine-to coarse-grained, interbedded with siltstone and claystone.	Sand	√	√	√	√	√	√
Jurassic	Amran Group	Marl /Shale succession; more marly-at the top, locally evaporitic.	Carbonates	√	√	√	√	√	–
			Gypsum	√	√	√	√	√	–
Precambrian	Basement Complex	Granite, gabbro and metamorphic rocks.	Substitutes	–	√	–	√	√	–

*Am=Amran, Bj=Bajel, Br=Al-Barh, Lh=Lahj, Ab=Abyan, Mk=Al-Mukalla

The workability and durability of the cement raw materials quarries are controlled by three main factors [1]. These are: (i) the spatial characteristics of their exposures (e.g. altitude, topography, shape, size and extension); (ii) the quality of raw materials (e.g. their physical and chemical properties); and (iii) the geologic setting and outcrop characterization, such as high elevations, steep slopes, rugged topography, heterogeneity in bed thickness, lithologic composition, presence of igneous bodies, intensive fracturing and jointing and abundance of karstification features [1]. However, in several quarry sites, the designed quarrying plans are not applied perfectly as a result of various geological complications.

Global cement production was 4.1 billion tonnes in 2020 with a growth rate of 24% from its highest in 2010 [22]. The cement industry confronts significant challenges in raw materials, energy demands, and CO_2 emissions reduction, which are global and local environmental concerns [23]. Exhaustion of the earth’s non-renewable resources is a growing dilemma because energy consumption has rapidly increased during the 21st century [24]. As the cement plants quarrying sector is widely active, at some time in the future, the reserves of non-renewable resources will inexorably be diminished as they are extracted from the environment and used for economic purposes. Non-renewable resources are finite in quantity and their stocks do not regenerate after they are quarried [25]. The continuous harvesting of natural resources exposes us to permanent economic deterioration such as biodiversity loss, global warming, climate change, vegetation degradation, ecosystem destruction, river damage and dust contamination [24, 26, 27]. Dust emissions are a major source of environmental pollution during quarrying operations; for example, dust is generated during drilling, blasting, loading, transportation and unloading of cement raw materials. The emission of dust and other pollutant gases reduces the quality of air which affects the healthy lifestyle of the population.

To produce PC, raw materials should be combined, and in consequence, an open quarrying method is used for quarrying [25]. Blasting is a standard quarrying procedure to excavate raw materials. The uncontrolled blasting technique has produced unstable rock slope faces [28]. Geo-environmental problems identified in abandoned quarry sites are slope stability problems such as sliding, toppling and the quality of rock mass [29]. Due to improper blasting design, the excessive over-blasting has caused the widening of major joints, excessive over breaks, and unstable and loose overhanging blocks [30, 31]. This situation can pose a threat to the environment and a hazard to people because it creates an unstable environment.

Although the processes of quarrying and related operations commonly result in significant environmental hazards, few geo-environmental studies have been carried out on the cement raw materials quarrying sites in Yemen. Al-Khirbash and El-Anbaawy [32] presented valuable data about the Tertiary and Quaternary volcanic eruptions and the water, petroleum and mineral resources in Yemen. They gave a brief profile of the natural geo-environmental hazards. USAID [33] assessed the environmental hazards of the Amran Cement Plant (ACP) located in western Yemen. They led stakeholders and governmental authorities to recognize the environmental, social and economic impacts of the existing plants and proposed expansion facilities. Also, they proposed a number of appropriate controls and mitigation and monitoring measures and emphasized the importance of increasing awareness about the plant and its environmental impacts. Al-Anweh [19] described the industrial sites of the ACP with emphasis on the raw material quarrying sites, the hazardous sites of manufacturing processes, and waste disposal areas to determine the potential industrial impacts and their proposed mitigation measures. He proposed an environmental management plan including monitoring of the mitigation measures and achievement and management of hazardous waste as well as conservation of raw materials, water resources and energy use.

Generally, natural resources, whether renewable or non-renewable, are subject to depletion if they are used in an improper way on a sustained basis. However, no previous work has examined the conservation of these resources in the presently exploited cement raw materials quarries in Yemen.

This study aims at: (i) evaluating the geology of the currently exploited quarry sites and their environs; (ii) documenting the quarrying conditions and geological complications; (iii) evaluating the environmental hazards resulting from the processes of quarrying and related operations; and (iv) outlining a number of recommendations concerning the means of dealing with these complications and hazards.

2. Methodology

The thirty six quarry sites studied are situated in the region lying between longitudes 42°55'-49°30'E and latitudes 13°00'-15°10'N (Figure 1). They were grouped into three geographic sectors; the western sector (A) which comprises the Amran, Bajel, and Al-Barh areas, the southwestern sector (B) which includes Abyan and Lahj, and the southern sector (C) which is represented by the Al-Mukalla area. It is important to mention that each of these sectors has its own physiographic and geologic characteristics (Table 1).

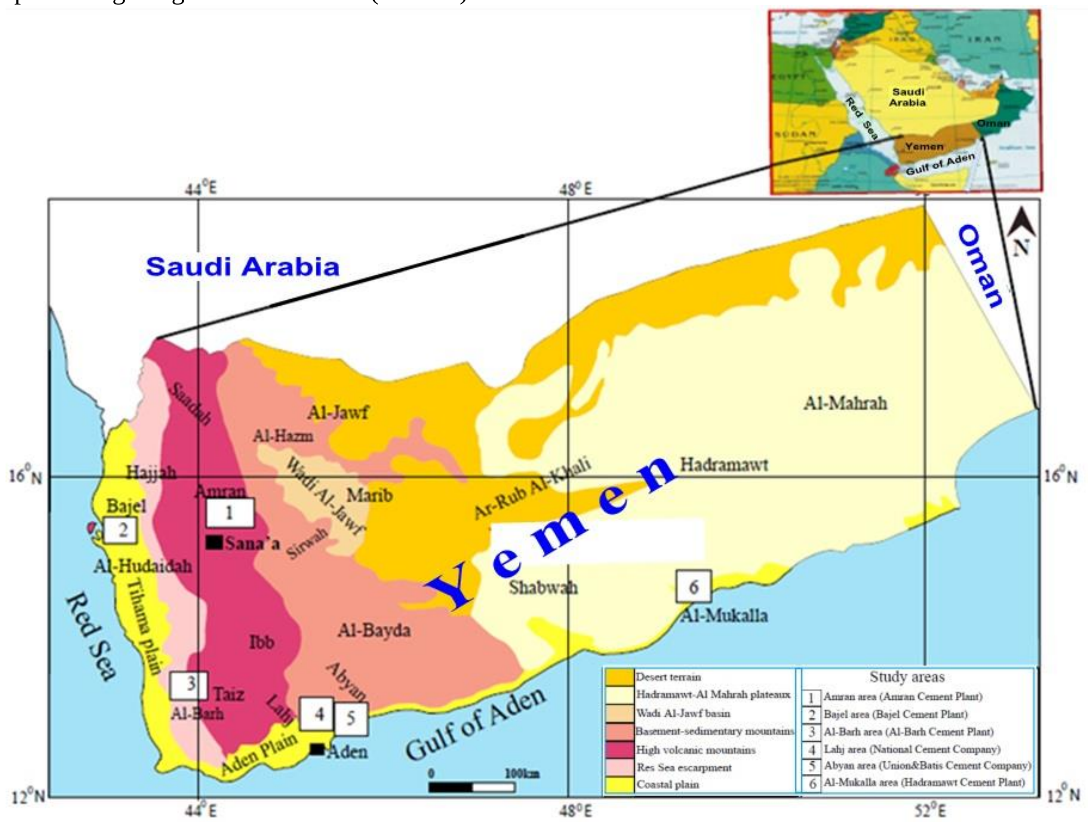

Figure 1. Location and physiographic map of Yemen showing the sites of the main cement plants [7].

The geological background of the studied quarry sites is based on the information reported in the works conducted by [8, 34-36]. These works included mapping of the quarry sites and their vicinities as well as description of the rock successions in bore holes and trenches. Additionally, the basic data included topographic maps (1:50,000), geologic maps (1:250,000), and satellite images.

Comprehensive field work was conducted to construct detailed geologic maps and cross sections of the six quarry sites. Sampling and lithologic descriptions of selected representative stratigraphic sections of the raw materials within the quarries and their vicinities were also investigated. Moreover, the quarrying conditions, including the types of openings of the quarry faces, as well as the slope and stability of the escarpments, were assessed. In addition to the assessment of the geological and geotechnical complications currently faced or likely to be faced in the future, the geo-environmental hazards of the quarries and their environs were documented and evaluated.

The locations of the selected stratigraphic sections and sites were defined by using the Global Positioning System (GPS) and verified by classified satellite images. Image processing was conducted using ERDAS Imagine (8.5), a remote sensing technique on a personal computer platform. The Geographic Information System (GIS) was developed to produce the maps using Arc GIS (10.1).

3. Geologic Setting

3.1 The carbonate quarries

The detailed geological characteristics of the carbonate successions in the quarry sites studied are summarized in Table 2 and the stratigraphic sections of the carbonate raw materials exploited from the different lithologic layers in all the quarries studied are given in Tables 3-8.

Table 2. Summary of the geological characteristics of the carbonate successions in the various quarry sites [1].

Area	Quarry	Rock unit			Lithologic unit	Lithology	Main structural features
Amran	J. Al-Merhah (old and new)	Amran Group	Madbi Fm.		Uppermost	Marly and chalky limestone	Several fault blocks, gentle-plunging folds, fractures, and karstification cavities
					Upper	Intercalations of mudstone, dolomitic limestone and fossiliferous marl	
					Middle	Limestone intercalated with marl and chalky limestone	
					Lower	Rubbly marl intercalated with thick mudstone layers	
			Shuqra Fm.	Thoma Mb.	Upper	Reefal limestone intercalated with marly limestone	
				W. Nahm Mb.	Lower	Marl, mudstone, cherty dolomitic limestone	
Bajel	J. Maais, J. Shawkan, Flaifilah		Madbi Fm.		Unit 6	Cherty limestone, well-bedded, fossiliferous	Different types of faults, minor folds, fractures, highly-weathered dykes and sills
					Unit 5	Thinly-bedded limestone alternating with pyritic shale	
					Unit 4	Interbedded blocky limestone and shale	
			Shuqra Fm.	Thoma Mb.	Unit 3	Thickly-bedded, cavernous, bioclastic limestone	
				W. Nahm Mb.	Unit 2	Thinly-bedded, cherty, dolomitic limestone	
					Unit 1	Marly limestone intercalated with bituminous and pyritic shale	
Al-Barh	J. Al Awgaa		Madbi Fm.		Unit 6	Intercalations of marl and shale	Tilted beds, major faults, volcanic sheets and dykes
					Unit 5	Well-bedded clayey and chalky limestone	
			Shuqra Fm.	Thoma Mb.	Unit 4	Reefal limestone	
				W. Nahm Mb.	Unit 3	Thinly-bedded sandy limestone	
					Unit 2	Limestone with chert bands and nodules, fossiliferous	
					Unit 1	Dolomitic limestone, slightly sandy	
Abyan	J. Al-Hizz		Nayfa Fm.		Upper	Massive limestone interbedded with marl, fossiliferous	Abundant fracturing and brecciation
					Lower	Massive dolomitized limestone, with chert nodules	
	J. Hattat		Nayfa Fm.		Upper	Alternating massive and brecciated limestones	Joints and karstification caves (commonly filled with gypsum)
					Lower	Brecciated limestone	
Lahj	J. Sa'am		Shuqra Fm.	W. Nahm Mb.	Upper	Nodular, cherty limestone interbedded with sandstone	Faults, fractures karstification caves, altered basaltic and doleritic dykes
					Middle	Alternating well-bedded chalky limestone and cavernous concretional limestone	
					Lower	Dolomitic limestone	
Al-Mukalla	Al-Eoon (Abdullah Gharib)	Hadramawt Group	Umm er Redhuma Fm.			Thinly-bedded chalky limestone intercalated with marl or massive dolomitic limestone, fossiliferous	Faults, fractures and karstification

In the Amran area, the carbonate raw materials used in ACP are exploited from two quarries (old and new) in Jabal Al-Merhah. Abu-Zaid *et al.* [2] reported that these carbonates belong to the Jurassic Shuqra and Madbi formations; the former is thicker and more widespread (Figure 2a). The Shuqra carbonates are composed of marl intercalated with calcareous mudstone and cherty or dolomitic marly limestone (Wadi Nahm member) overlain by reefal and marly limestones (Thoma member) (Figures 3a and b). The Madbi Formation, on the other hand, consists of (from base to top): rubbly marl intercalated with calcareous mudstone, interbedded limestone and marl grading upwards to chalky limestone, intercalations of mudstone, marly dolomitic limestone and marl, and interbedded marly and chalky limestones [1] (Figure 3c). The stratigraphic section of the carbonate raw materials exploited from the different lithologic layers in the Amran quarries are given in Table 3. The Amran carbonate successions are characterized by the presence of several fault blocks associated with gentle folds or elongated single-or double-plunging noses. The fold wings have very gentle dips (5°-10°) (Figures 2a and 3d) and the fold axes are generally aligned parallel or perpendicular to the trends of fault blocks (Figure 2b). The latter have resulted from normal faults having different directions and scales, forming several grabens and horsts. Oblique or strike-slip faults separate the old and new quarries.

Table 3. Stratigraphic section of the different carbonate layers in Amran quarry.

Elevation (m) a.s.l.	Rock unit			Petrographic Group	Sample No	Lithology	workable zone	Thick. (m)	Chemical composition (%)					Rock name
									CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	
2440, 2430 0m	Amran Group	Madbi Formation	Upper	III	Am-26		A	14.90	48.80	4.80	1.60	0.90	1.80	Limestone
2420, 2410	Amran Group	Madbi Formation	Middle	II	Am-25		B	23.55	43.70	5.90	1.90	1.40	4.40	Marly dolostone
2400	Amran Group	Madbi Formation	Lower	I	Am-24		C	10.87	6.20	56.30	12.30	6.00	1.20	Marly mudstone
2390	Amran Group	Madbi Formation	Lower	I	Am-23		D	4.60	23.10	32.20	10.30	4.90	1.60	Marly mudstone
	Amran Group	Madbi Formation	Lower	I	Am-22		E	4.52	48.60	4.90	1.70	1.40	1.80	Limestone
2380	Amran Group	Madbi Formation	Lower	V	Am-21		F	7.56	23.40	23.60	8.50	4.20	7.20	Marly dolostone
	Amran Group	Madbi Formation	Lower	V	Am-20		G	3.48	50.70	2.60	0.80	1.90	2.20	Limestone
2370	Amran Group	Madbi Formation	Lower	V	Am-19		H	12.06	24.20	25.70	9.90	4.80	3.80	Marly dolostone
2360	Amran Group	Madbi Formation	Lower	V	Am-18		I	4.00	9.60	47.20	14.90	5.70	1.70	Mudstone
2350, 2340	Amran Group	Shuqra Formation	Thoma member	III	Am-17		J	21.07	48.40	4.50	1.50	1.10	2.40	Limestone
	Amran Group	Shuqra Formation	Thoma member	III	Am-16		K	5.07	36.00	16.60	5.80	3.00	2.30	Marly limestone
2330	Amran Group	Shuqra Formation	Thoma member	III	Am-15		L	2.94	4.30	58.90	13.40	4.40	1.60	Mudstone
	Amran Group	Shuqra Formation	Thoma member	III	Am-14		M	2.55	32.40	20.60	7.10	3.80	1.60	Marly limestone
2320, 2310	Amran Group	Shuqra Formation	Thoma member	III	Am-13		N	19.02	46.60	7.30	2.50	1.40	1.40	Limestone
2300	Amran Group	Shuqra Formation	Thoma member	V	Am-12		O	5.87	35.70	17.10	6.50	2.80	1.90	Marly limestone
	Amran Group	Shuqra Formation	Thoma member	V	Am-11		P	3.69	26.40	26.00	8.10	4.30	5.60	Marly dolostone
2290	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-10		Q	7.12	35.80	15.60	5.90	2.70	3.60	Marly limestone
	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-9		R	6.34	48.60	4.90	1.60	1.10	1.70	Limestone
2280	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-8		S	9.11	36.30	15.60	5.70	2.90	2.80	Marly limestone
2270	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-7		T	5.11	29.00	22.90	10.00	3.50	2.10	Marly limestone
	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-6		U	6.11	37.80	15.10	5.10	2.30	3.10	Marly limestone
2260	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-5		V	6.67	49.30	5.10	1.60	1.00	1.40	Limestone
2250	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-4		W	3.77	36.90	15.40	5.20	2.90	3.70	Marly limestone
	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-3		X	2.56	46.60	7.30	2.50	1.40	1.40	Limestone
2240	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-2		Y	11.35	47.60	5.50	1.90	1.30	3.20	Marly dolostone
	Amran Group	Shuqra Formation	Wadi Nahm member	I	Am-1		Z	2.55	13.90	37.90	13.00	6.20	3.70	Limestone

I- Foraminiferal lime mudstone-wackestone **II- Foraminiferal packstone-grainstone**
II- Foraminiferal packstone-grainstone **IV- Pel-oolitic packstone-grainstone**
V- Dolomitized wackestone-dolostone

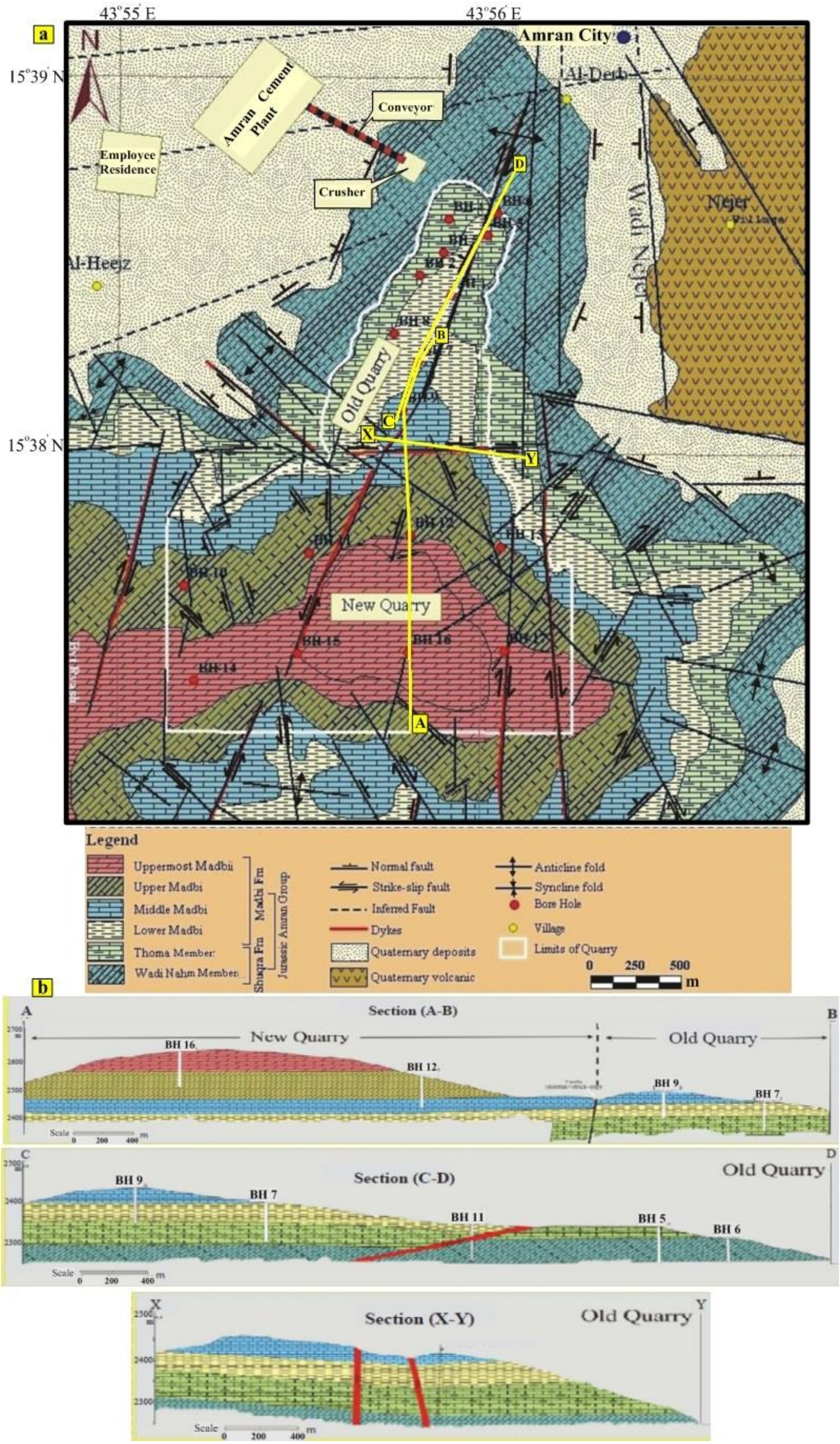

Figure 2. a) Detailed geological map of the old and new quarry sites of Amran Cement Plant [19], and b) Geologic cross-sections in the quarry sites [19].

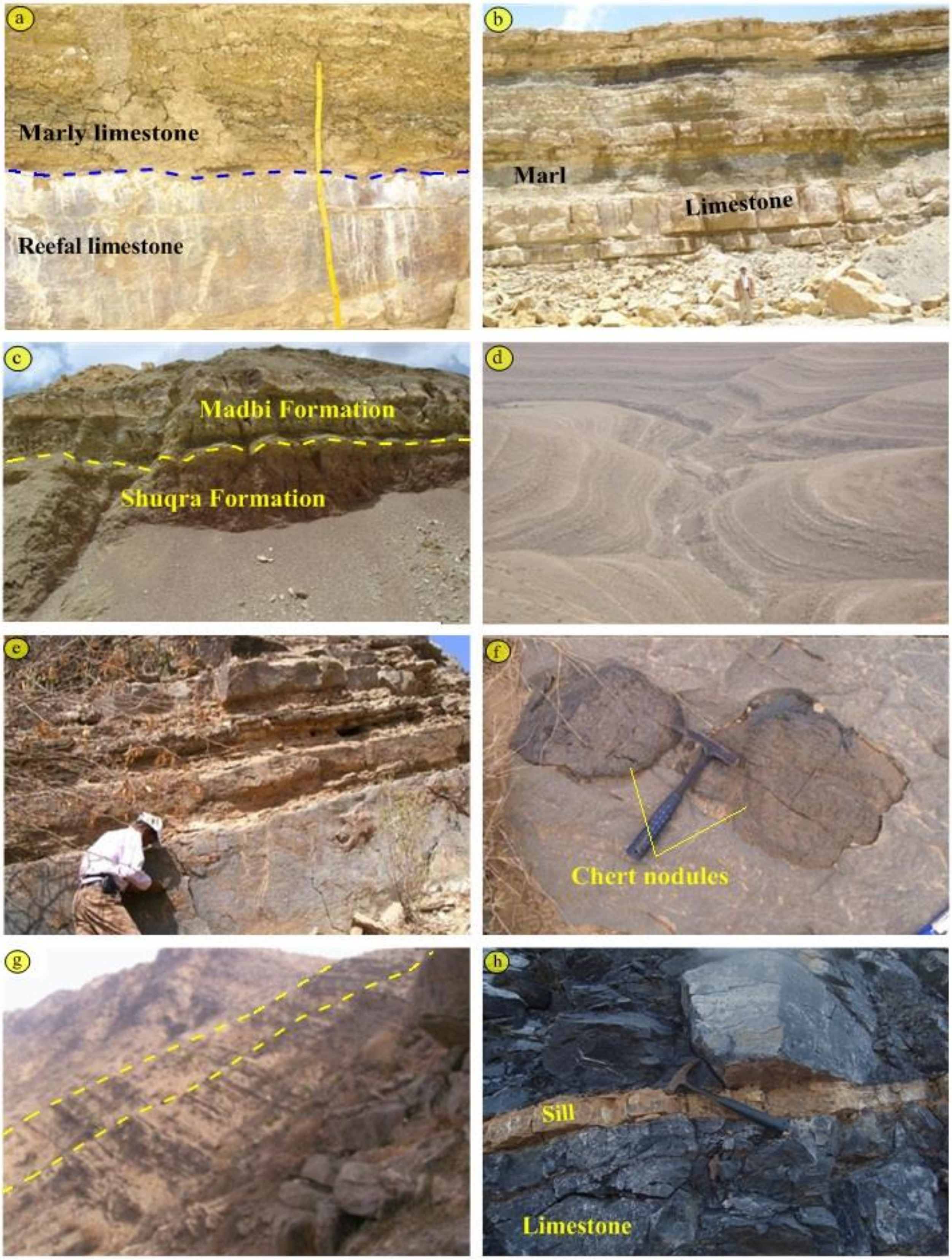

Figure 3. Field photographs of the quarries of carbonate raw materials, a) The contact between the marly and reefal limestones in the uppermost part of the Shuqra Formation (Amran area), b) Interbeds of marl and limestone in Wadi Nahm member (Amran area), c) Marly and chalky limestone of the Madbi Formation overlying the eroded top of the Shuqra Formation (Amran area), d) Major folds in the Amran Group (Amran area), e) Thickly-bedded limestone in Wadi Nahm member (Bajel area), f) Scattered chert nodules in the limestone of Wadi Nahm member (Bajel area), g) Normal faults (Bajel area), h) Volcanic sill in Madbi Formation (Bajel area).

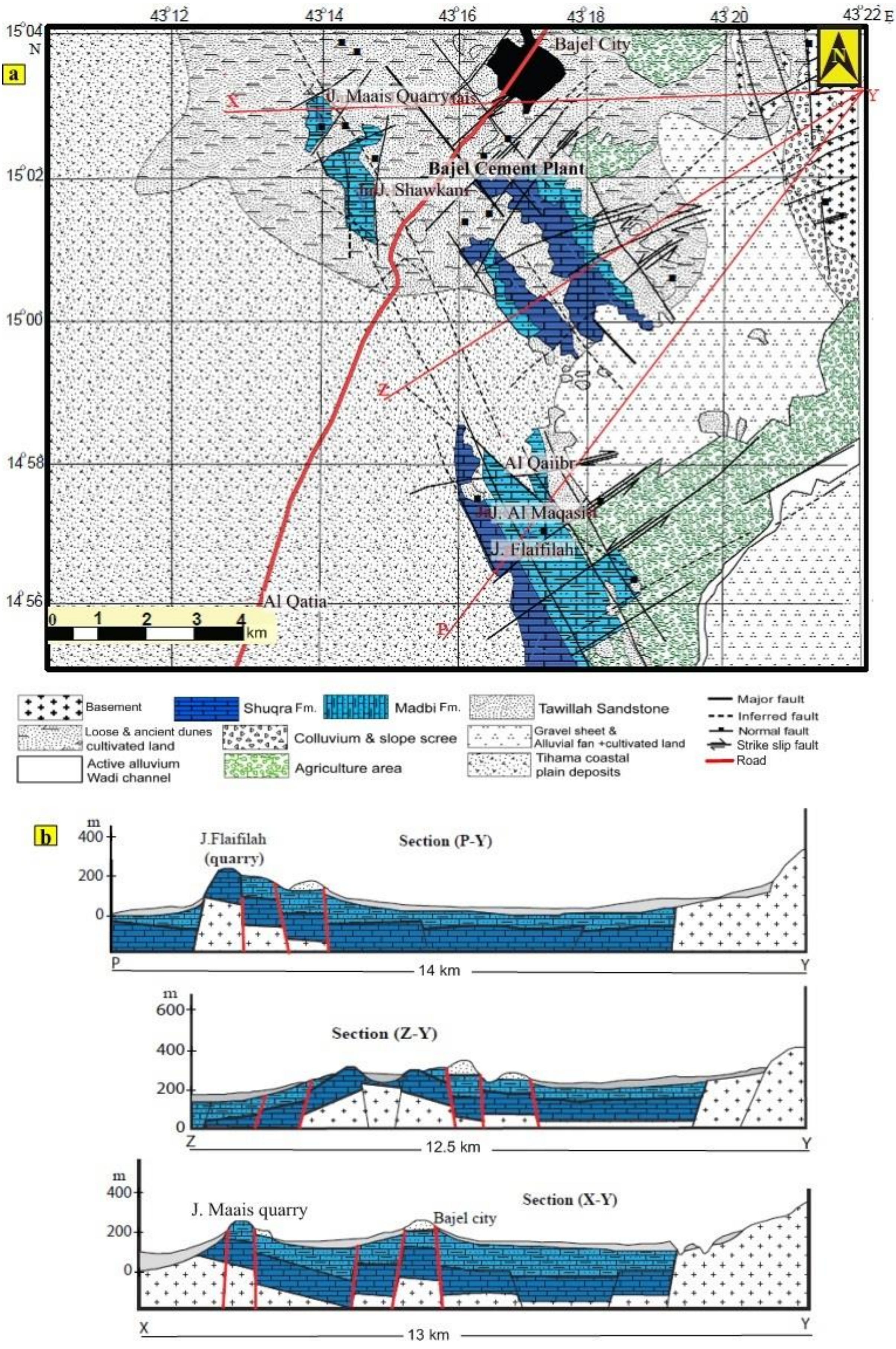

Figure 4. a) Detailed geological map of the quarry sites in the Bajel area, and b) Geologic cross-sections in the quarry sites.

The carbonate succession in the Bajel area belongs to the Shuqra and Madbi formations (Figure 4a). The former rock unit is represented by (from base to top): limestone interbedded with marly limestone containing pyritic and bituminous bands (unit 1), intercalations of limestone and cherty limestone occasionally alternating with dolostone and marl layers (unit 2), and bioclastic and oolitic limestones (unit 3) (Figures 11e and f). The Shuqra carbonate succession is intensively faulted and fractured and contains basic volcanic sills and dykes. The Madbi Formation, on the other hand, is made up of (from base to top): marl interbedded with limestone and calcareous shale (unit 1), limestones which are occasionally marly or shaley (unit 2), and partly cherty limestone (unit 3). The stratigraphic section of the carbonate raw materials exploited from the different lithologic layers in Bajel quarry are given in Table 4. The succession forms cliffs which are highly steep at their western sides while their eastern sides have low to moderate angles of slope (15°-40°). Faults are common, mainly trending NW and NNW (Figures 3g and 4a) and forming grabens and horsts (Figure 4b). Step faults and NE and ENE oblique or strike-slip faults represent the most dominant type in the Flaifilah quarry site (Figure 3b). Monoclines and synclinal and anticlinal folds (Figure 4b) as well as basic sills and dykes are common (Figure 3h).

Table 4. Stratigraphic section of the different carbonate layers in Bajel quarry.

Elevation (m) a.s.l.	Rock unit			Petrographic group	Sample No	Lithology	workable zone	Thick. (m)	Chemical composition (%) CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Rock name
245 240 235 230 225 220 215 210 205 200 195 190 185 180 175 170 165 160 155 150	Amran Group	Madbi Formation		I	Bj-10		A	9	53.9	1.24	0.498	0.258	0.718	Pure limestone fossil
				I	Bj-3		B	9	51.4	5.2	1.7	1.1	1.1	Sandy limestone
							C	10	53.4	2.5	0.1	0.5	0.7	Sandy limestone
							D	7	52.26	7.44	1.68	1.11	0.96	Sandy limestone
				I	Bj-2		E	10	52.14	3.66	1.16	0.46	0.59	Silty limestone
		Shuqra Formation	Thoma member	II	Bj-19		F	8.5	53.6	1.3	0.5	0.4	0.9	Fossiliferes limestone
							G	9	53.1	2.3	0.8	0.2	0.6	Fossiliferes limestone
							H	5.5	51.0	4.0	1.3	0.8	0.6	Fossiliferes limestone
			Wadi Nahm member	I	Bj-18		J	8.5	46.2	8.5	3.0	1.6	2.4	Limestone
				I	Bj-17		K	9	48.4	6.0	2.0	1.4	1.5	Limestone
				II	Bj-16		L	1.5	53.1	2.3	0.8	0.2	0.6	Fossiliferes limestone
				V	Bj-15		N	14	44.17	7.16	1.57	1.17	4.74	Marly dolostone

I- Foraminiferal lime mudstone-wackestone; II- Foraminiferal packstone-grainstone; III- Skeletal packstone-grainstone; IV- Pel-oolitic packstone-grainstone; V- Dolomitized wackestone-dolostone

The carbonate succession in the Al-Barh area (Jabal Al-Awgaa quarries) belongs to the Shuqra and Madbi formations (Figure 5a). The former rock unit consists of (from base to top): sandy dolomitic limestone (unit 1), dolomitic cherty limestone (unit 2), sandy limestone (unit 3), partly dolomitized or silicified reefal limestone (unit 4) and slightly argillaceous, occasionally chalky limestone (unit 5). The Madbi succession, on the other hand, is made up of shale and marl intercalated with cherty marly limestone (Figure 6a). The stratigraphic section of the carbonate raw materials exploited from the different lithologic layers in Al-Barh quarry are given in Table 5. Structurally, the carbonate succession constitutes a main horst or ridge which is bounded by major intersecting faults trending NNW and NNE (Figure 5a and b). These faults affect the wings of major synclinal and anticlinal folds the axes of which extend mainly S-N (Figures 5a and b). They form a plunging structure to the north of Jabal Al-Awgaa. The cores of the synclinal folds are commonly occupied by the Cretaceous Tawilah sandstone succession which is highly faulted and contains numerous dykes. On the other hand, the cores of the anticlinal folds are occupied by the Jurassic Shuqra Formation which is bounded at the fold wings by gently-tilted beds of the Madbi Formation (Figure 5b). The limestone ridge in the Al-Barh area has steep cliffs particularly at its northern and eastern borders in the eastern side of the quarry where the Tawilah outcrops are intruded by a large mass of the Tertiary alkaline granite. In the western side of the ridge, volcanic sediments and basaltic sheets of the Tertiary Trap Series are exposed. Numerous basic and intermediate dykes are present in both the carbonate succession (Figure 6b) and the Tertiary igneous rocks.

Table 5. Stratigraphic section of the different carbonate layers in Al-Barh quarry.

Elevation(m) a.s.l.	Rock unit	Petrographic group	Sample No	Lithology	workable zone	Thick. (m)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Rock name
720–715	Amran Group; Madbi Formation	I	Br-10		A	9	47.05	8.22	2.06	1.23	1.5	Limestone
710–705	Amran Group; Madbi Formation	I	Br-17		B	9	45.90	12.30	1.79	1.25	0.88	Limestone
700	Amran Group; Madbi Formation	I	Br-18		C	9	49.40	7.55	1.21	0.67	0.81	Limestone
695	Amran Group; Madbi Formation	II	Br-19		D	3	53.25	3.45	0.31	0.35	0.38	Silty limestone
690–685	Amran Group; Madbi Formation	I	Br-13		E	12	53.72	5.67	1.64	1.05	1.27	Silty limestone
680–670	Amran Group; Shuqra Formation; Thoma member	II	Br-11		F	12	44.52	16.72	0.843	0.854	0.816	Marly limestone
	Amran Group; Shuqra Formation; Thoma member	II	Br-11		G	3	54.25	1.20	0.42	0.19	0.60	Fossiliferes limestone
665–655	Amran Group; Shuqra Formation; Wadi Nahm member	I	Br-15		I	12	43.1	15.2	2.5	1.3	1.2	Marly limestone
650	Amran Group; Shuqra Formation; Wadi Nahm member	I	Br-15		J	6	14.94	36.89	11.34	4.97	7.13	Marly limestone dolomite
	Amran Group; Shuqra Formation; Wadi Nahm member	V	Br-21		K	3	44.9	17.1	1.1	0.7	1.0	Marly limestone
645	Amran Group; Shuqra Formation; Wadi Nahm member	V	Br-21		L	2	14.9	36.9	11.3	5.0	7.1	Marly limestone dolomite
	Amran Group; Shuqra Formation; Wadi Nahm member	V	Br-21		M	3	29.9	27.0	6.2	2.8	4.1	Marly dolostone
640–635	Amran Group; Shuqra Formation; Wadi Nahm member	V	Br-9		O	3	44.2	7.5	2.0	1.3	4.4	Marly limestone dolomite
630	Amran Group; Shuqra Formation; Wadi Nahm member	V	Br-6		P	3	35.1	11.1	2.9	1.4	9.6	Marly dolostone

Chemical composition (%)

I- Foraminiferal lime mudstone-wackestone II- Foraminiferal packstone-grainstone
III- Skeletal packstone-grainstone IV- Pel-oolitic packstone-grainstone
V- Dolomitized wackestone-dolostone

Table 6. Stratigraphic section of the different carbonate layers in Abyan quarry.

Elevation (m) a.s.l.	Rock unit	Petrographic group	Sample No	Lithology	workable zone	Thick. (m)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Rock name
405–400	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-15		A	1	30.48	1.55	0.16	0.09	0.49	Marly mudstone
395	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-13d		B	6	41.24	6.10	0.94	0.33	0.47	Marly limestone
390–385	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-13c		C	9	40.65	14.65	3.52	1.71	1.75	Marly limestone
380	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-13b		D	3	30.80	21.40	2.70	1.70	0.60	Marly mudstone
375	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-13a		E	6	36.48	7.79	2.18	1.03	0.63	Marly limestone
370	Amran Group (Nayfa Formation); Upper Nayfa	II	Ab-7		F	6	55.08	0.68	0.12	0.20	0.21	Silty limestone
365	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-2		G	6	53.46	0.83	0.25	0.14	1.42	Silty limestone
360–355	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-3		H	9	45.83	9.44	3.20	0.97	1.32	Limestone
350–340	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-10		I	12	44.60	11.54	3.79	1.22	1.10	Marly limestone
335	Amran Group (Nayfa Formation); Upper Nayfa	I	Ab-11		J	9	45.85	10.14	3.14	1.05	1.18	Limestone
330–325	Amran Group (Nayfa Formation); Lower Nayfa	II	Ab-16		K	12	54.20	0.76	0.06	0.09	0.22	Fossiliferes limestone
320–310	Amran Group (Nayfa Formation); Lower Nayfa	IV	Ab-9		L	12	55.19	0.41	0.07	0.10	0.26	Fossiliferes limestone
305–305	Amran Group (Nayfa Formation); Lower Nayfa	IV	Ab-8		M	12	54.67	0.76	0.20	0.18	0.30	Fossiliferes limestone
300	Amran Group (Nayfa Formation); Lower Nayfa	IV	Ab-5		N	1	45.14	9.08	2.79	39.63	1.17	Marly mudstone
295–290	Amran Group (Nayfa Formation); Lower Nayfa	IV	Ab-12		O	9	54.67	0.76	0.20	0.18	0.29	Sandy limestone
285–280	Amran Group (Nayfa Formation); Lower Nayfa	IV	Ab-12		P	9	55.19	0.41	0.06	0.01	0.26	Sandy limestone
275	Amran Group (Nayfa Formation); Lower Nayfa	IV	Ab-12		Q	9	54.95	0.83	0.16	0.10	0.26	Sandy limestone
270–260	Amran Group (Nayfa Formation); Lower Nayfa	V	Ab-1		R	9	43.82	4.52	1.32	1.00	6.79	Marly limestone

Chemical composition (%)

I- Foraminiferal lime mudstone-wackestone II- Foraminiferal packstone-grainstone
III- Skeletal packstone-grainstone IV- Pel-oolitic packstone-grainstone
V- Dolomitized wackestone-dolostone

In the Abyan area, the carbonate successions belong to the Nayfa Formation and, less commonly, the underlying Madbi and Shuqra formations (Figures 7a and b). The Shuqra carbonates are composed of limestone whereas those of the Madbi Formation consist of calcareous mudstone intercalated with limestone and sandy marl.

The Nayfa succession, on the other hand, is made up of interbedded dolomitic limestone, brecciated limestone and cherty limestone (unit 1) overlain by interbeds of limestone, marly limestone and, in places, oolitic and karstified limestone (unit 2). The stratigraphic section of the carbonate raw materials exploited from the different lithologic layers in Abyan quarry are given in Table 6. Structurally, the carbonate succession in Jabal Al-Hizz forms mountain ridges extending from Wadi Bana to Wadi Hassan with a total length of more than 40 km. The succession rests unconformably on the eroded surfaces of the Precambrian basement rocks (Figure 7b). It forms highly dipping monoclinal folds trending WSW-ENE (Figure 6c). The scarp slopes of the mountains follow the bedding of the carbonate layers which dip about 30° to the SE (Figures 6d and 7b). The whole area is affected by faults trending NW, NNW and ENE and their zones are commonly filled with secondary gypsum.

In the Lahj area, the carbonate succession belongs to the Shuqra Formation which rests unconformably on the Precambrian basement rocks (Figures 8a and b). The rest of the Jurassic Amran Group seems to have been eroded and its place is taken by the Tertiary Trap Series. The succession consists of (from base to top): dolomitic limestone (unit 1), chalky and concretional limestone (unit 2) and cherty limestone containing thin sandstone laminae (unit 3). The carbonate raw materials exist mainly within the Al-Sa'am quarries where they overlie the granitic mountains (Jabal Sa'am) (Figure 8b).

Table 7. Stratigraphic section of the different carbonate layers in Lahj quarry.

Elevation (m) a.s.l.: 580, 575, 570, 565, 560, 555, 550, 545, 540, 535, 530

Rock unit	Petrographic group	Sample No	Workable zone	Thick. (m)	Chemical composition (%) CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Rock name
Amran Group; Shuqra Formaition (Wadi Nahm member)	I	Lh-4	1	3	50.13	6.00	1.14	0.660	1.00	Limestone
	III	Lh-12	2	9	54.31	1.59	0.294	0.185	0.338	Fossiliferes limestone
	II	Lh-5	3	3	44.36	10.96	3.26	1.29	1.58	Marly limestone
		Lh-2	5	6	50.13	6.00	1.14	0.66	1.00	Limestone
	IV	Lh-18	7	6	39.44	24.81	1.01	0.933	0.793	Marly limestone
		Lh-1	8	6	29.16	45.45	0.39	1.14	0.24	Marly mudstone
	V	Lh-11	9	2	38.46	4.24	1.32	0.94	24.28	Dolostone
			10	3	42.86	2.92	0.41	0.45	19.66	Dolostone
			11	6	27.00	21.69	2.96	1.55	11.47	Dolostone
		Lh-7	12	3	30.37	5.42	0.83	0.94	18.11	Dolostone
		Lh-17	13	6	37.2	10.34	1.14	1.06	9.68	Dolostone
		Lh-21	15	6	23.38	19.91	5.39	1.62	14.00	Dolostone

I- Foraminiferal lime mudstone-wackestone; II- Foraminiferal packstone-grainstone; III- Skeletal packstone-grainstone; IV- Pel-oolitic packstone-grainstone; V- Dolomitized wackestone-dolostone

The stratigraphic section of the carbonate raw materials exploited from the different lithologic layers in Lahj quarry are given in Table 7. The carbonate outcrops are dissected by faults having a general NW-SE strike (Figures 8a and b). Noticeable shearing and shifting of rocks in different directions has resulted in the creation of fractures along bedding planes trending N to NW and dipping 10°-20° NE. Several basaltic and doleritic dykes are recorded (Figure 6e).

In the Al-Mukalla area, the carbonate raw materials are exploited mainly from the Al-Mukalla quarry which is located to the south of the Abdullah Gharib area (El-Eoon). These carbonates belong to the Paleocene Umm er Radhuma Formation (Hadramawt Group) (Figure 9a) which disconformably overlies the Cretaceous Al-Mukalla Formation (Figure 9b). In both the limestone escarpment and drilled boreholes, the Umm er Radhuma carbonate succession is composed of thinly-bedded chalky limestone intercalated with marl or massive dolomitic limestone (Figure 6f).

The chalky limestone commonly contains iron oxide spots and microfossils. The dolomitic limestone is fine-grained, hard, and commonly massive and contains very few cavities. Some limestone intervals are thinly-bedded, moderately friable, fossiliferous and contain black iron spots, a few calcite veinlets and clay-filled cavities (Figure 6f). The stratigraphic section of the carbonate raw materials exploited from the different lithologic layers in Al-Mukalla quarry are given in Table 8. Structurally, the Cretaceous and Tertiary sequences in the quarry area were subjected to uplifting by WSW-ENE trending faults which resulted in the development of a series of sub-parallel scarps and back-slopes in which the beds dip S-ESE (Figure 9b). In addition, minor N-S trending faults are recorded within the wadi channels. There are several regional transfer zones with small vertical displacements. Also, the entire succession is highly fractured and jointed and contains karstification features at the top of the workable face of the quarry.

3.2 The sand-clay quarries

The sand-clay raw materials are exploited from the Cretaceous Tawilah and Al-Mukalla Sandstones, the Eocene Rus Formation, and the Quaternary wadi deposits which are represented mainly by cultivated and/or reclaimed land for agriculture (Figures 10a-e). The Tawilah sandstone quarry area forms a horst with steep-sloped mountains adjacent to the Amran carbonate plateaux where thick zones of calcareous and kaolinitic fine-grained sandstone lenses are randomly quarried in the Bajel area (Figure 10f). The quarried outcrops of the Al-Mukalla Sandstone form hillocks within the wadi plain of Abyan Delta.

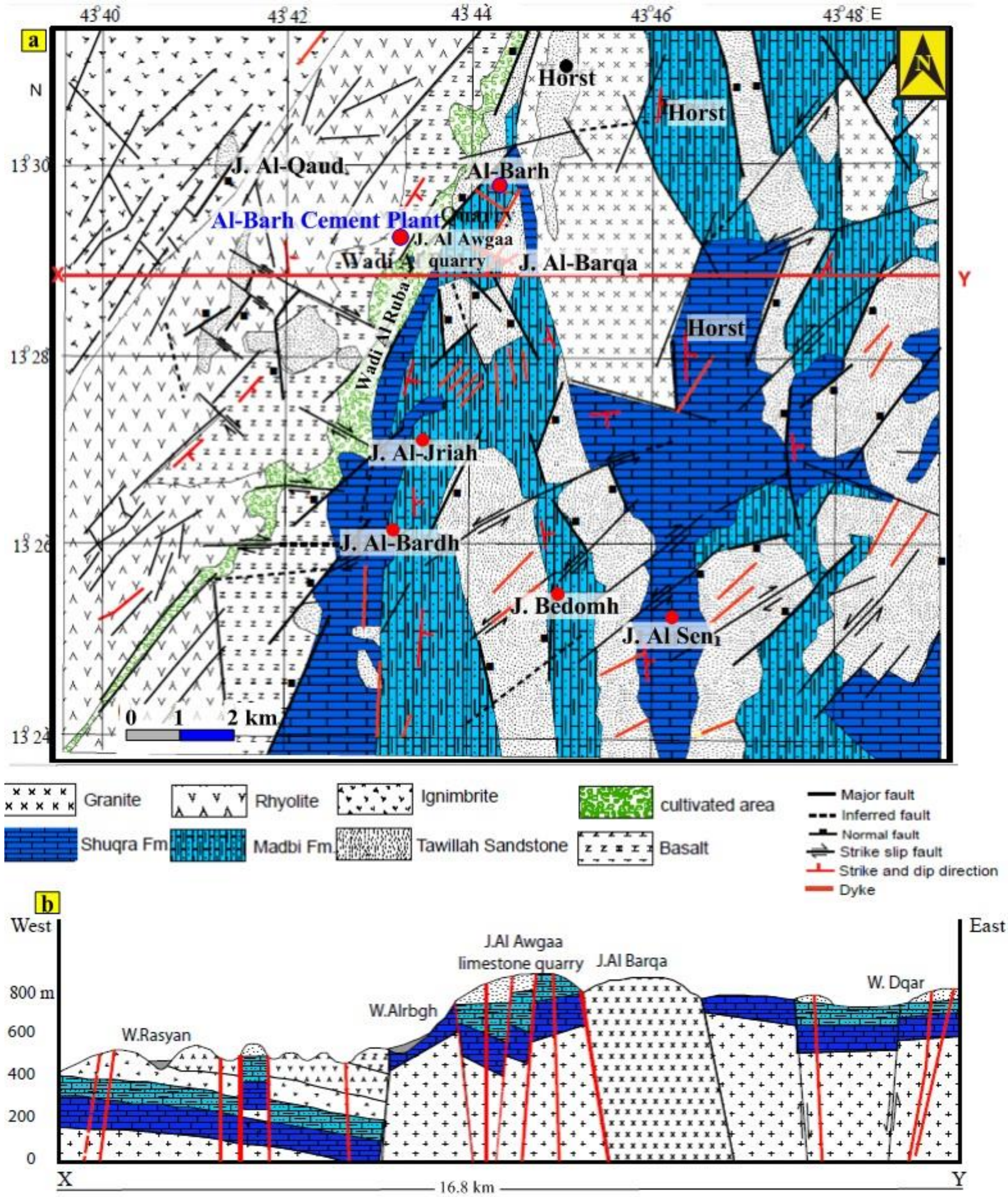

Figure 5. a) Detailed geological map of the quarry sites in the Al-Barh area, and b) Geologic cross-section in the quarry sites.

Figure 6. Field photographs of the quarries of carbonate raw materials, a) Intercalations of marl, chalky limestone and calcareous shale in the Madbi Formation (Al-Barh area), b) Eroded dykes cutting Madbi Formation (Al-Barh area), c) Steeply-dipping monoclinal folds in the Amran succession (Abyan area), d) Amran carbonate layers showing a high angle of dip (Abyan area), e) A basic dyke cutting carbonate rocks (Lahj area), f) Chalky limestone intercalated with massive dolomitic limestone of the Umm er Radhuma Formation (Al-Mukalla area).

3.3 The gypsum quarries

The gypsum raw materials are exploited from the Jurassic Sab'atayn Formation in Al-Ghiras, the Miocene evaporites in Bajel and Al-Barh areas and the Eocene Rus Formation in the Al-Mukalla area. Also, they are quarried from the Upper Eocene-Oligocene Rimah Formation in Al-Mahfed quarry for the Lahj and Abyan cement plants. The open-cut quarry face consists of a succession of halite beds intercalated with pyritic black shale and overlain by the quarried gypsum-anhydrite bed. The latter forms an updomal structure as a result of diapirism and folding of the underlying halite-shale succession.

3.4 The correctives and additives quarries

The corrective and additive raw materials are represented by the Tertiary and Quaternary volcanic materials as well as some iron-rich basement rocks. The cement factories in Bajel and Al-Barh get scoria from the Quaternary Amran- Sana'a volcanic fields while those in the Abyan, Lahr, and Al-Mukalla areas exploit scoria and volcanic tuff from the Quaternary Aden Volcanic Series in the Shuqra and Belhaf-Bir Ali volcanic fields. The majority of the quarried volcanic cones in these fields are low conical-shaped, have well-developed craters and are covered by or associated with volcanic bombs, lapilli tuff and ashes. On the other hand, the basement rocks in the Abyan and Lahj areas are the main source of iron ores which are used as corrective materials. The iron-rich minerals exist in basic dykes and sills which are very common in the basement rocks and the Jurassic carbonates in several localities.

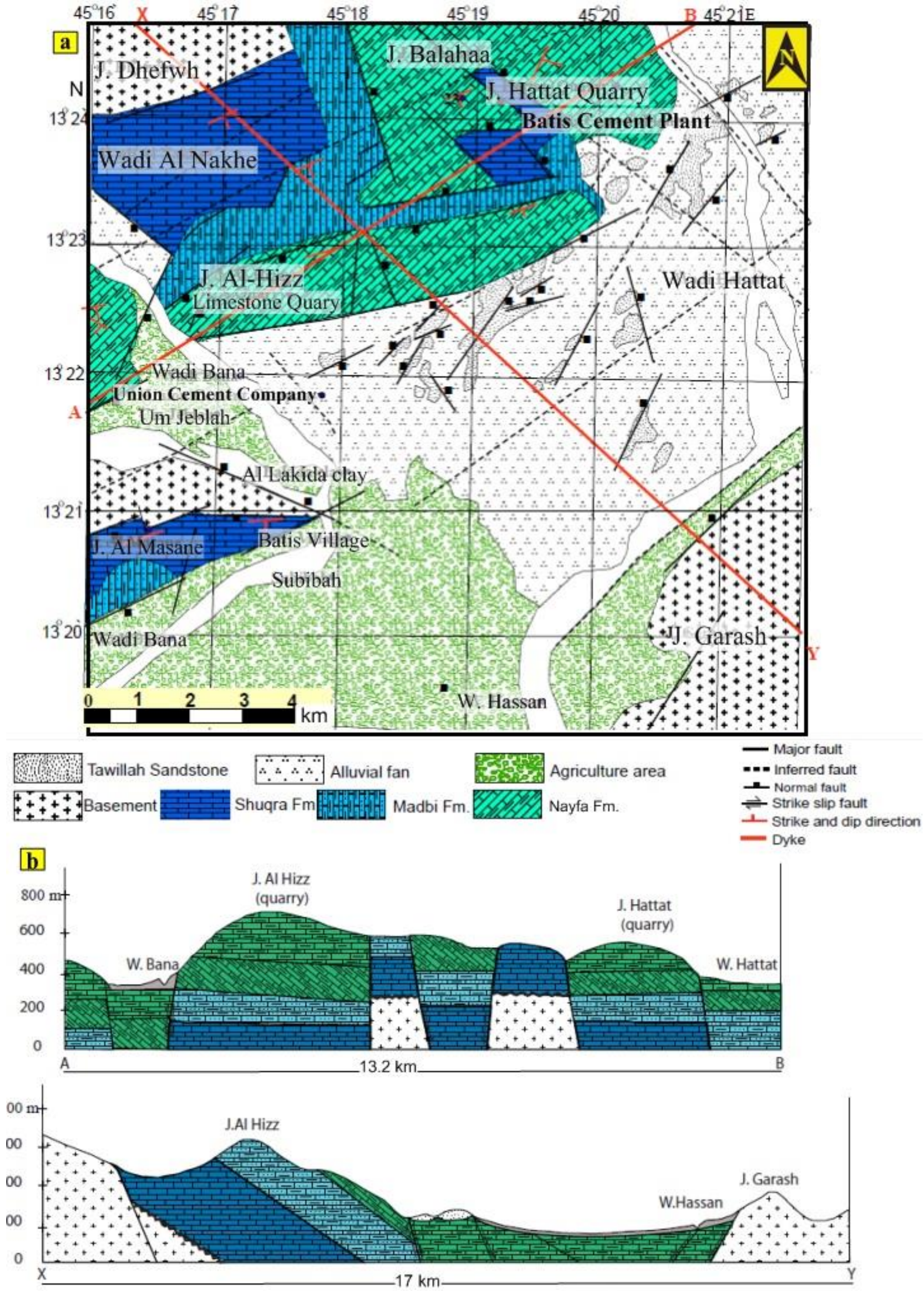

Figure 7. a) Detailed geological map of the quarry sites in the Abyan area, and b) Geologic cross-sections of the quarry sites.

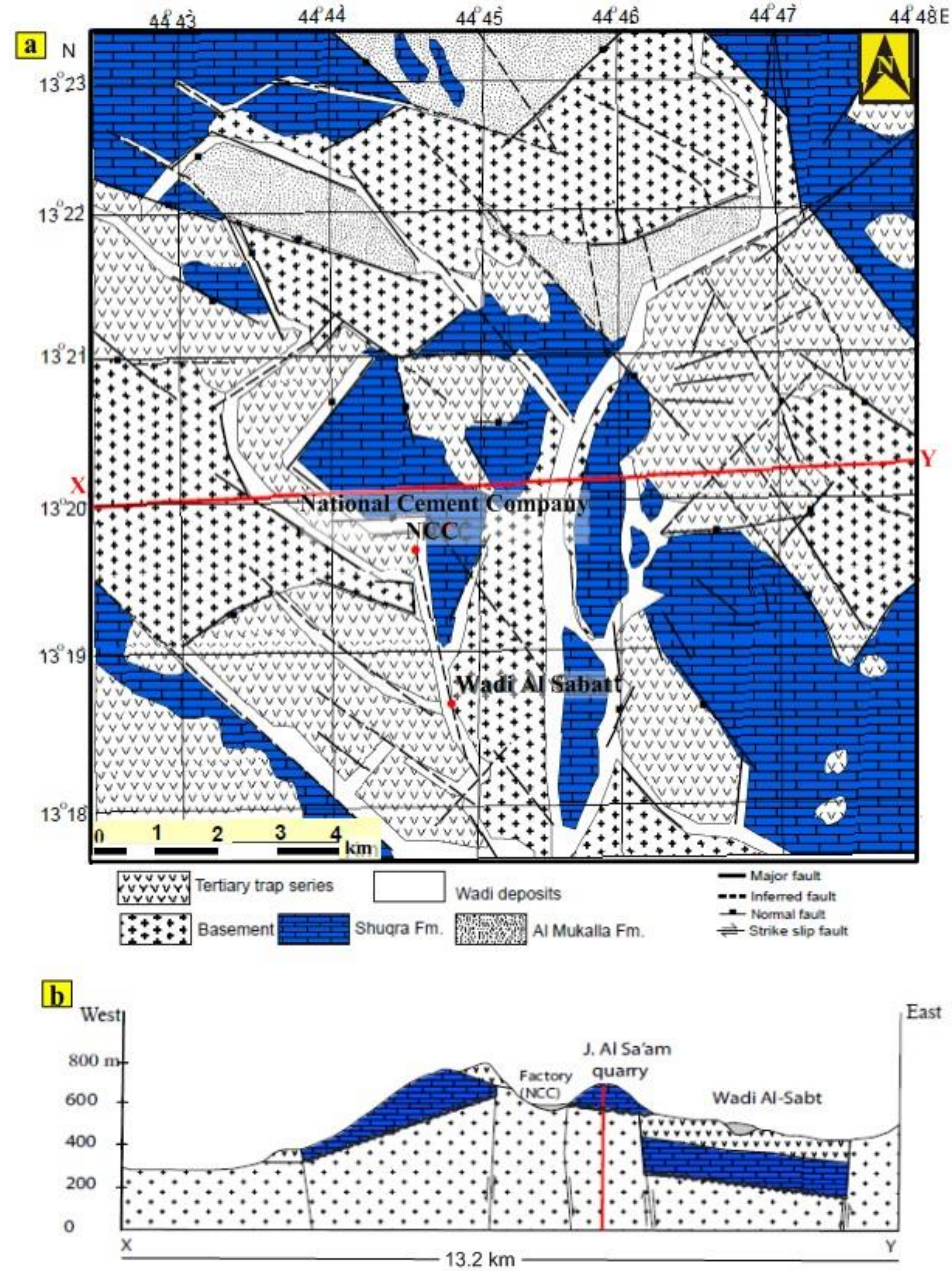

Figure 8. a) Detailed geological map of the quarry sites in the Lahj area, and b) Geologic cross-section in the quarry sites.

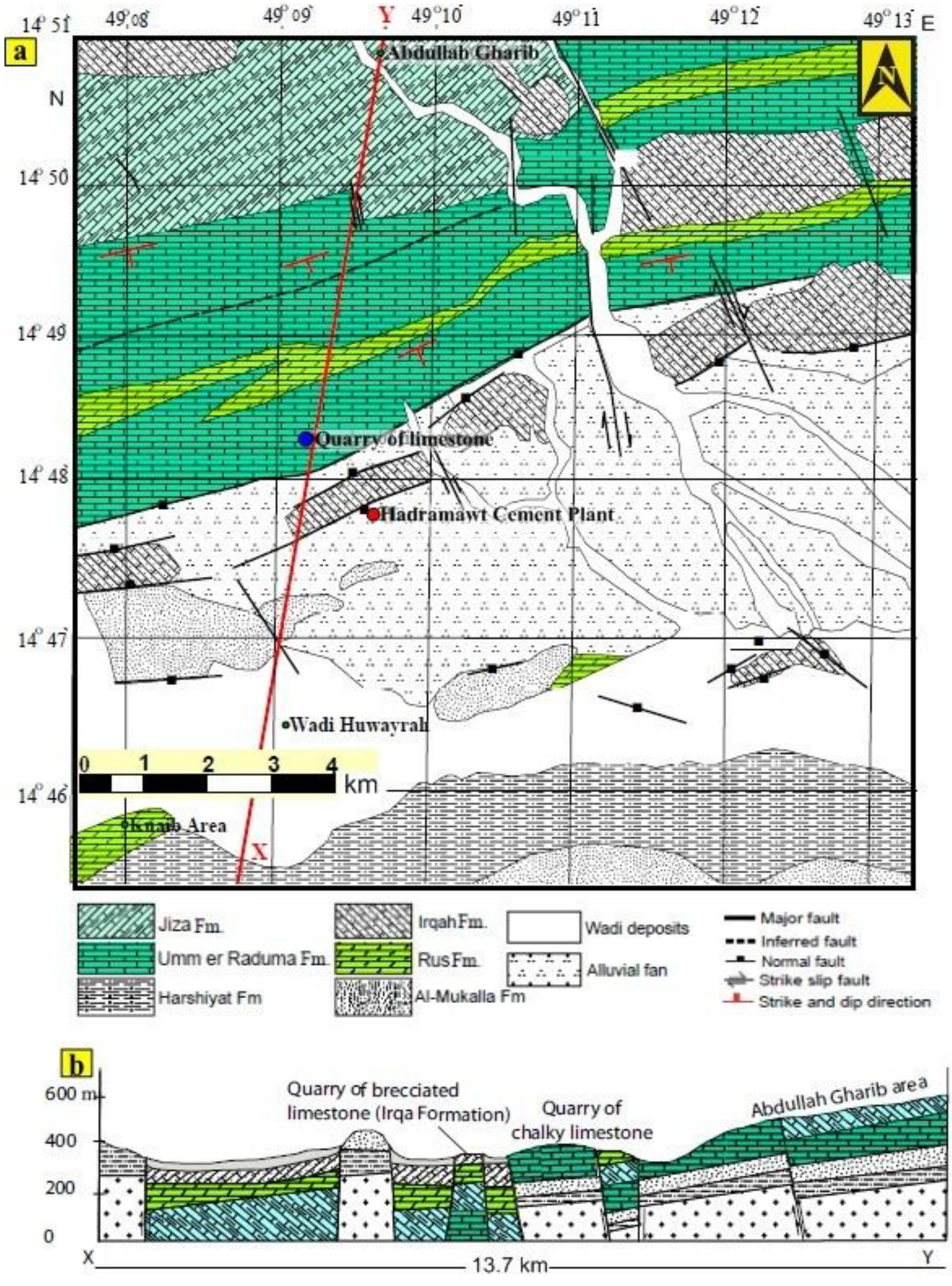

Figure 9. a) Detailed geological map of the quarry sites in the Al-Mukalla area, and b) Geologic cross-section in the quarry sites.

4. Quarrying Methods and Conditions

4.1 The carbonate quarries

The carbonate raw materials in all the studied sites are quarried applying the open method (step-quarry operation) or classic multiple bench open quarrying by means of drilling and blasting. Working through several faces with up to ~70^{o} inclination, bench heights not more than 30 m (usually 15 m) and bench width ~15 m keeps the quarry under control during all steps of excavation. The development of quarrying systems for carbonate raw materials involved opening the quarry top-down from the top of a hill (block), where drilling levels and bench heights were first designed (Figure 11a).

Table 8. Stratigraphic section of the different carbonate layers in Al-Mukalla quarry.

Rock unit	Petrographic group	Sample No	workable zone	Thick. (m)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Rock name
Hadramawt Group, Umm er Radhuma Fm.	II	Hd-6	A	3	23.83	54.66	0.38	0.23	0.676	Mudstone
	II	Hd-24	B	9	50.19	1.72	0.55	0.27	3.27	Limestone
	II	Hd-24	C	9	50.65	3.11	0.82	0.43	1.34	Limestone
	II	Hd-7	D	6	54.97	0.861	0.159	0.108	0.282	Chalky limestone
	V	Hd-5	J	3	33.19	1.31	0.265	0.0612	18.51	Dolostone
	V	Hd-13	M	9	29.64	0.689	0.158	3.64	19.57	Dolostone
	II	Hd-8	E	12	55.32	0.44	0.10	0.05	0.23	Chalky limestone
	II	Hd-8	F	12	55.02	0.67	0.165	0.0509	0.302	Chalky limestone
	II	Hd-9	G	12	55.32	0.441	0.0951	0.0521	0.229	Fossiliferes limestone
	II	Hd-23	H	12	46.34	1.20	0.46	0.72	6.58	Limestone
	II	Hd-18	I	9	54.59	1.02	0.362	0.0986	0.332	Fossiliferes limestone
	II	Hd-4	L	9	37.54	21.54	4.94	1.7	1.72	Marly limestone

Elevation (m) a.s.l.: 360 (top) to 250 (base). Lithology column shown graphically.

I- Foraminiferal lime mudstone-wackestone; II- Foraminiferal packstone-grainstone; III- Skeletal packstone-grainstone; IV- Pel-oolitic packstone-grainstone; V- Dolomitized wackestone-dolostone

4.2 The sand-clay quarries

The Tawilah sandstones are quarried by means of bottom-hole blasting and manual use of pneumatic hammers since the required quantity of sand is extremely small. On the other hand, the clay-marl deposits in Al-Mukalla quarry are quarried using the classic multiple-bench open method (drilling and blasting). The Quaternary soft soil clay and sandy clay which constitute alluvial benches on flat wadi plains are quarried from open pits by advancing a single bench of 3 to 10 m in height (Figure 11b). Commonly, the quality distribution pattern of these deposits demands vertical cutting of the bench using a hydraulic excavator. Its operating level is the top surface from which the bench can be cut upwards so that strata of various qualities can be mixed.

4.3 The gypsum quarries

The gypsum raw materials in Kulagah and Thoma (Amran area), Salif (Bajel and Al-Barh areas), Al-Mahfed (Lahj and Abyan areas) and Kuaib (Al-Mukalla area) quarries are commonly quarried applying single-bench open mining by manual use of pneumatic hammers, blasting and excavation using wheel loaders (Figure 11c).

4.4 The correctives and additives quarries

Both the Quaternary pyroclastics which consist of loose to agglomerated scoria or tuff and the iron ore in the metamorphosed Precambrian Basement rocks are excavated using a combined artisanal quarrying on a small scale. All materials are exploited by using open pit surface quarrying by manual use of pneumatic hammers and hand tools (Figure 11d). Blasting is performed from time to time to fractionize the rocks.

5. Geological Complications

Several geological complications were recorded in the presently exploited quarries of cement raw materials. These include: (i) high elevation, steep slopes and rugged topography; (ii) tilting of beds; (iii) intensive fracturing; (iv) heterogeneity in the deposit lithology and thickness; (v) presence of igneous sills and dykes some of which are intensively weathered; and (iv) abundance of karstification features (mainly dissolution cavities).

In some cases, cement raw materials are found in mountains with high elevations and steep slopes, which makes quarrying conditions very difficult (Figure 12a). For example, the Jabal Sa'am limestone succession (~60 m thick) in the Lahj area overlies a hill of granitic basement rocks which is about 590 m (a.s.l.) (Figure 12b). Furthermore, the limestone deposits in Al-Hizz quarry (Abyan area) are confined to ridges with steep slopes (30°-32°) accompanied by steep dip angles (80°-85°) (Figure 12c). Similarly, in the Bajel area, steep slopes (15°-30°) of some carbonate plateaux have a negative impact on the quarrying conditions.

Figure 10. Field photographs of the quarries of sand-clay raw materials, a) Sand-clay deposits in Thuqban quarry (Amran area), b) Silty sand exposed (Bajel area), c) Sand-clay raw materials exploited (Abyan area), d) Hillocks of medium-to-coarse grained, compact and very hard sandstone (Abyan area), e) Claystone and mudstone intercalated with thin marl and marly limestone layers of the Rus Formation (Al-Mukalla area), f) Fine-grained, calcareous and kaolinitic sandstone lenses in Tawilah Group (Bajel area).

Tectonic tilting of beds and intensive faulting and fracturing represent a major problem in quarrying carbonates and gypsum in their sites [1]. Also, the presence of sills and dykes may cause rapid structural changes. At Al-Mahfed and Kuaib gypsum quarries in the Al-Mukalla area; the beds have medium angles of dip (about 25°), which makes quarrying difficult. The carbonate beds in Jabal Sa'am (Lahj area) have smaller dip angles (10° and 20°) but are very steep in places due to structural deformation caused by intensive faulting. In the Bajel quarry site, the normal faults and associated open extension fractures (Figure 12d) are active structures which accelerate landsliding on the plateau slopes. Also, the presence of numerous intersecting fractures and joints in most carbonate quarry sites, particularly at Lahj and Abyan (Figure 12e), facilitates the mechanical and chemical weathering of rocks.

Heterogeneity in bed thickness and lithologic composition is very common in all the studied quarries, especially those of carbonate raw materials. This heterogeneity has resulted in marked differences in the intensity, type and direction of joints between the limestone beds and the calcareous shale and marl interbeds (Figure 12f) as well as between the basement rocks and the tilted overlying limestone strata (Figure 12b). In the Amran carbonate quarry sites, the relatively harder limestone intercalations and interbeds are characterized by more intense and closely-spaced fractures and joints than the overlying and underlying calcareous mudstone and marl. The differences in lithology and, hence, the intensity of fracturing have resulted in marked variations in the extent of weathering, which has caused the development of rugged topography.

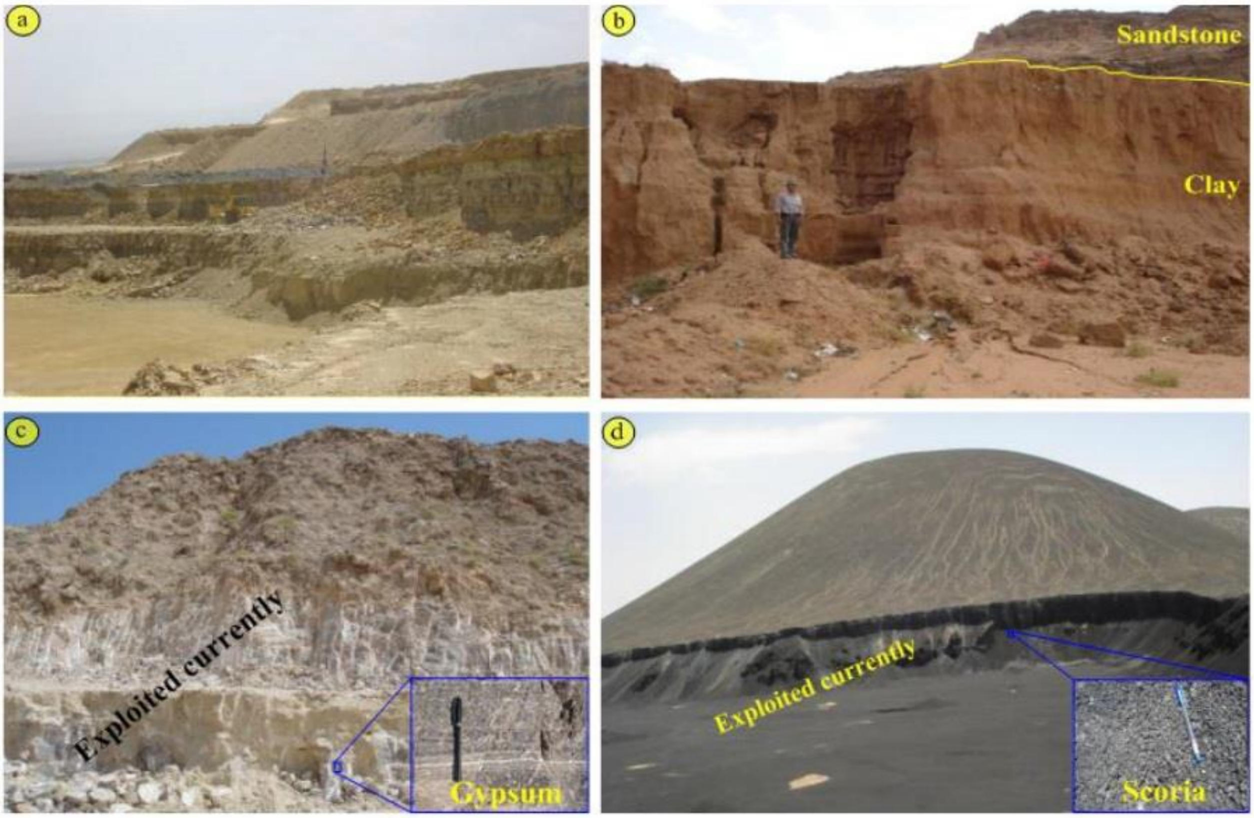

Figure 11. Field photographs showing the applied methods of quarrying the cement raw materials, a) Proper exploitation of a carbonate succession. The quarry was opened from the hill top after designing bench heights (Amran area), b) Open pit quarrying in a succession of Quaternary soft soil clay overlain by a thick section of sand in the Thqban sand-clay quarry (Amran area), c) Single-bench open mining of a section of gypsum and fine clastics in the Kuaib gypsum quarry (Al-Mukalla area), d) Open pit surface quarrying of a pyroclastic cone in a scoria quarry in the Amran-Sana'a volcanic field (Amran area).

The difficulties of quarrying, particularly of Madbi and Nayfa carbonates as well as the Tawilah (Al-Mukalla) sandstones, are connected with both the presence of vertical and horizontal volcanic sills and dykes and the intensity of the relatively recent faults. These difficulties become more significant with the increase in the intensity of weathering and lithologic alterations as well as the structural deformations which accompanied the intrusion of sills and dykes. In Bajel and Al-Barh quarries, for instance, the entire carbonate succession contains sills and, less commonly, dykes of intensively-weathered volcanics which often enclose fragments of the wall rocks. In these quarries, several trials were made to get rid of these volcanic bodies and obtain almost pure carbonate materials (Figure 12g).

In all the studied quarry sites, karstification features, particularly solution cavities and sink holes, are developed both in the carbonate rock surfaces and along joints and fractures as a result of heavy rainfall and prolonged chemical weathering (Figure 12h). The developed karstification and the presence of various heterogeneous filling materials has led to irregularity in the mountain slopes and heterogeneity in the composition of the raw materials.

6. Environmental Hazards

The hazards during the quarrying of the presently exploited cement raw materials are either natural or human-induced. Natural hazards are related to the topographic, geomorphologic and lithologic characteristics and tectonic setting of their outcrops, whereas artificial hazards are mainly created by the quarrying operations.

6.1 Natural geological hazards

Mass-wasting in the various quarry sites results mainly from land and overburden sliding, toppling, soil failure and rock fall. Land sliding is governed by a complex physical system which is controlled by factors such as slope morphometry (e.g. slope angle), the relationship between structural discontinuity and slope, differential weathering and exfoliation in relation to the lithological heterogeneity and the hydrological conditions including draining during quarrying processes. In this context, it was found that the limestone and sandstone quarry sites have low to moderate slopes while those of the basement rocks, volcanics and gypsum acquire moderate to steep slopes and, hence, are the most hazardous sites. Fractures are the structural elements which have the greatest effect on slope instability and land sliding. According to the orientation of the slope faces, the major structural trends affect the stability of slope and land sliding variably in different parts of the quarry site. In the highly-fragmented and weakly-cemented rocks, undercutting in the free slope faces are common due to differential weathering and erosion of interbedded strata that have different degrees of competence (such as limestones and marl). With these strata, there are significant signs of slope instability as erosion of softer beds causes the overlying harder material to drape, overhang and eventually slide or fall. The differential weathering associated with mass wasting has resulted in the formation of stepped scarps including flat tops, straight slopes and vertical free faces. In some quarrying sites, mass wasting, particularly land sliding and toppling, has been triggered by the increase in water pressure on joints and microfractures and/or by natural or artificial seismic activity. Moreover, the use of water during drilling for explosions has facilitated land sliding and rock fall in some quarries.

6.2 Quarrying operation hazards

The processes of quarrying, crushing and storage in the studied quarry sites have negative environmental impacts in a number of ways. These include: (i) active slope failure upon the free slope faces; (ii) formation of talus cones consisting of angular cobbles and rubbles which accumulates at the toe of high-steep slopes that are associated with falling of rock blocks during quarrying (Figure 13a); (iii) soil failure, rock fall and sliding of the clastic overburden particularly in gypsum quarries which are characterized by lithologic heterogeneity (Figure 13b); (iv) changes in topography of the overburden surfaces on mountain slopes due to quarrying using improper methods which have led to instability hazards (Figure 13c); (v) emission of dust which accumulates on vegetation and cultivated land leading to the reduction of the net photosynthesis and respiration rates resulting in lower primary production (Figure 13d); (vi) emission of noise that accompanies quarrying processes, especially explosions; (vii) accidental spillage and leakage of operational water during quarrying which has led to land sliding and/or flooding into the neighboring farm lands and residential areas (Figure 13e); and (viii) accidents that have resulted from collision with, or getting caught among the quarry tools and equipment during their mobilization. Generally, the quarrying processes in areas of gypsum and basement rocks are more hazardous than in those of carbonates and volcanics. On the other hand, no technical limitations were recorded in the clay quarry sites except for the degradation and loss of the valuable cultivated and/or reclaimed lands in almost all the sand clay quarry sites (Figure 13f).

7. Conclusion and Recommendation

The presently exploited quarries of cement raw materials in Yemen have several problems related to geological complications, environmental hazards and improper conservation of natural resources. The geological complications are represented mainly by the high elevations, steep slopes, rugged topography, heterogeneity in bed thickness, lithologic composition and quality, tilting of strata, presence of sills and dykes, especially in carbonate successions, intensive fracturing and jointing, and abundance of karstification features, especially solution cavities. Also, the processes of quarrying and related operations have negative environmental impacts in a number of ways. These include soil failure, overburden and land sliding, toppling and rock falls (which result in significant mass wasting), emission of dust and noise, and accidental leakage and spillage of operational water.

Generally, the quarrying operations are more hazardous in the quarries of gypsum and basement rocks than in those of carbonates and volcanics. On the other hand, problems related to the conservation of natural resources are represented primarily by the degradation of the valuable agricultural and reclaimed lands and improper exploitation of the cement raw materials as well as the fresh and underground waters.

To deal with the natural geological complications in the quarry sites, the following mitigation measures should be implemented : (i) reworking several faces with slope angles not more than 70^o and terraces not more than 30 m high within which storage of waste water is avoided; (ii) conducting careful excavation and rock cutting in successions characterized by rapid lateral and vertical variations in lithology and/or intensity of fracturing and jointing; (iii) reworking and compacting the loose overburden into several benches with acceptable slopes; (iv) conducting careful analysis of the ground stability and design of quarrying type and conditions in order to keep slope stability; (v) preparing mass movement inventories and hazard maps which are essential for designing the planning system of quarrying operations; (vi) instructing the engineers and workers about the formal planning process and the safe use of the quarry site; and (vii) monitoring and documenting the quarry site conditions through precise periodical field surveys to ensure the effective implementation of the mitigation measures.

Conservation of the natural resources can be achieved through: (i) optimizing the exploitation of the cement raw materials by applying computer-aided deposit evaluation and preparation techniques that can be utilized to plan optimal quarrying schemes according to the type, size, location and quality of the raw material; a commonly practiced resource-use technique is the block modeling of the quarry; (ii) all equipment of quarrying processes should be inspected and properly maintained for a safe working environment and for avoiding raw material wasting; (iii) preparing and implementing a sustainable plan of recycling both the fresh water supplied to the quarries and plants for drinking and cooling purposes and the already recycled water itself in order to keep their water demands at a minimum; (iv) avoiding excavation of the valuable agricultural and reclaimed lands by providing suitable alternative materials. These substitutes exist within the Jurassic and Tertiary carbonate-clastic successions (Amran and Al-Mukalla areas), the weathering materials of some volcanic dykes (Al-Barh area) and the basement rocks (Abyan and Lahj areas); (v) avoiding the accumulation of volumes of water on the quarry terraces; (vi) applying safety measures during transportation of the raw materials; (vii) inspecting and maintaining all the equipment used in quarrying operation; and (viii) prospecting for additional water resources. Additional water resources can be found in the alluvial deposits, the subsurface karstified limestones of the Amran Group and the Tertiary carbonate-clastic formations (such as those along the Amran Valley, the Abyan Delta plain and the coastal plain of Al-Mukalla area) and the Cretaceous Tawilah sandstone in Lakida and Hattat (Abyan area).

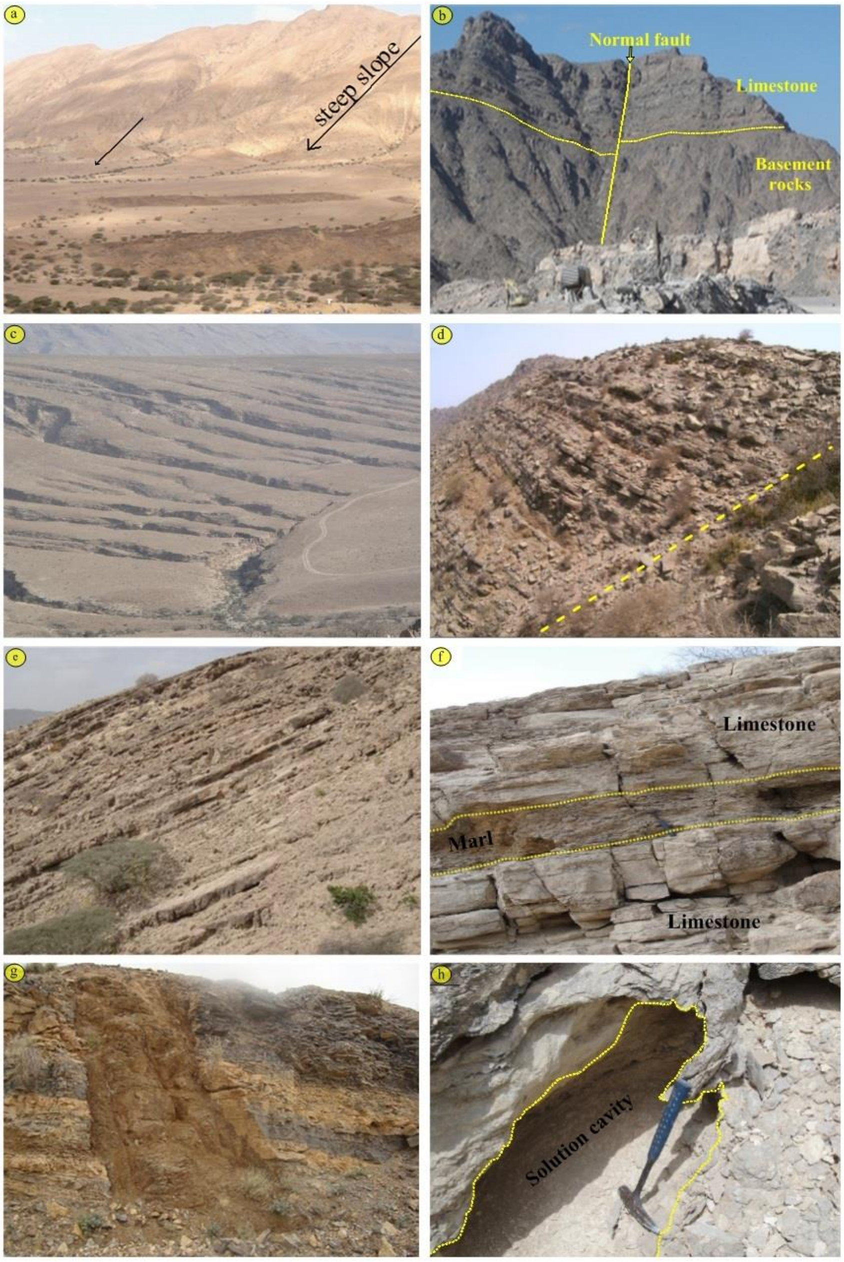

Figure 12. Field photographs showing some geological complications in the studied quarry sites, a) The high elevation, steep slopes, rugged relief and complex topography in Al-Hizz carbonate quarry (Abyan area), b) Rugged topography of a high hill made up of basement rocks by capped limestone in Jabal Sa’am (Lahj area), structural deformation resulting from intense faulting, c) Profound ridges and rugged topography in Al-Hizz carbonate quarry (Abyan area), d) Normal faults associated with open extension fractures in Bajel carbonate quarry (Bajel area), e) Extensive fractures and joints in highly-tilted beds in the Jabal Al-Hizz carbonate quarry (Abyan area), f) Difference in the intensity of jointing between limestone and marl interbededs in Al-Hizz quarry (Abyan area), g) An intensively weathered volcanic dyke in the limestone succession of Al-Barh carbonate quarry (Al-Barh area), h) Solution cavities in the Nayfa limestone in Jabal Al-Hizz carbonate quarry (Abyan area).

Figure 13. Field photographs showing some geo-environmental hazards in the studied quarry sites. a) Rock fall and sliding of the clastic overburden in a carbonate quarry in the Al-Mukalla area, b) Gypsum beds intercalated with, and overlain by, thin marl beds in the gypsum quarry in the Amran area, c) Steep slopes developed as a result of falling of separate rock blocks in the Al-Mukalla area, d) Dust emissions accompanying the explosion and other quarrying operations in the Lahj area, e) Accidental spillage and leakage of operational water during quarrying in the Al-Barh area, f) Excavation of agricultural soil in Al-Lakida clay quarry in the Abyan area.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of interest

The authors declare no conflict of interest.

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