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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 the presently exploited quarries 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 operations 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) and emission of dust and noise. 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 and the fresh and underground waters the reserves of which decreased drastically. 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 almost importance to conduct prospecting for new occurrences of the presently exploited cement raw materials and their possible substitutes as well as additional groundwater resources.

Introduction

The cement industry in Yemen is based on six main plants located in its western (Amran, Bajel, Al-Barh) and southern (Abyan, Lahj and Al-Mukalla) parts (Fig. 1). These plants produce about six million tons/year of the Portland Cement. 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. (2015) 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 Precambrian Basement rocks (Table 1). The stratigraphy and tectonic setting of these rock units were studied by several researchers (e.g., Beydoun, 1966; Grolier and Overstreet, 1978; Abu Khadra et al., 1984; El-Anbaawy, 1984; 1985a&b; Gotvald et al.,1988; Roberson Group,1992; Beydoun et al., 1998; Thomas, 2002; Al-Khirbash, 2003 and Al-Anweh, 2010 and 2015).

The workability and durability of the cement raw materials quarries are controlled by three main factors. 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) then geologic setting and complicating such as 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. However, in several quarry sites, the designed quarrying plans are not applied perfectly as a result of various geological complications.

In spite of the fact that the processes of quarrying and related operations commonly result in significant environmental hazards, however, few geoenvironmental studies were carried out on the cement raw materials quarrying sites in Yemen. Al-Khirbash and El-Anbaawy (1995) gave a brief profile of the natural geoenvironmental hazards. USAID (2005) assessed the environmental hazards of the Amran Cement Plant (ACP) located in western Yemen and proposed a number of controls and mitigation and monitoring measures. Al-Anweh (2010) evaluated the geoenvironmental aspects of ACP.

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

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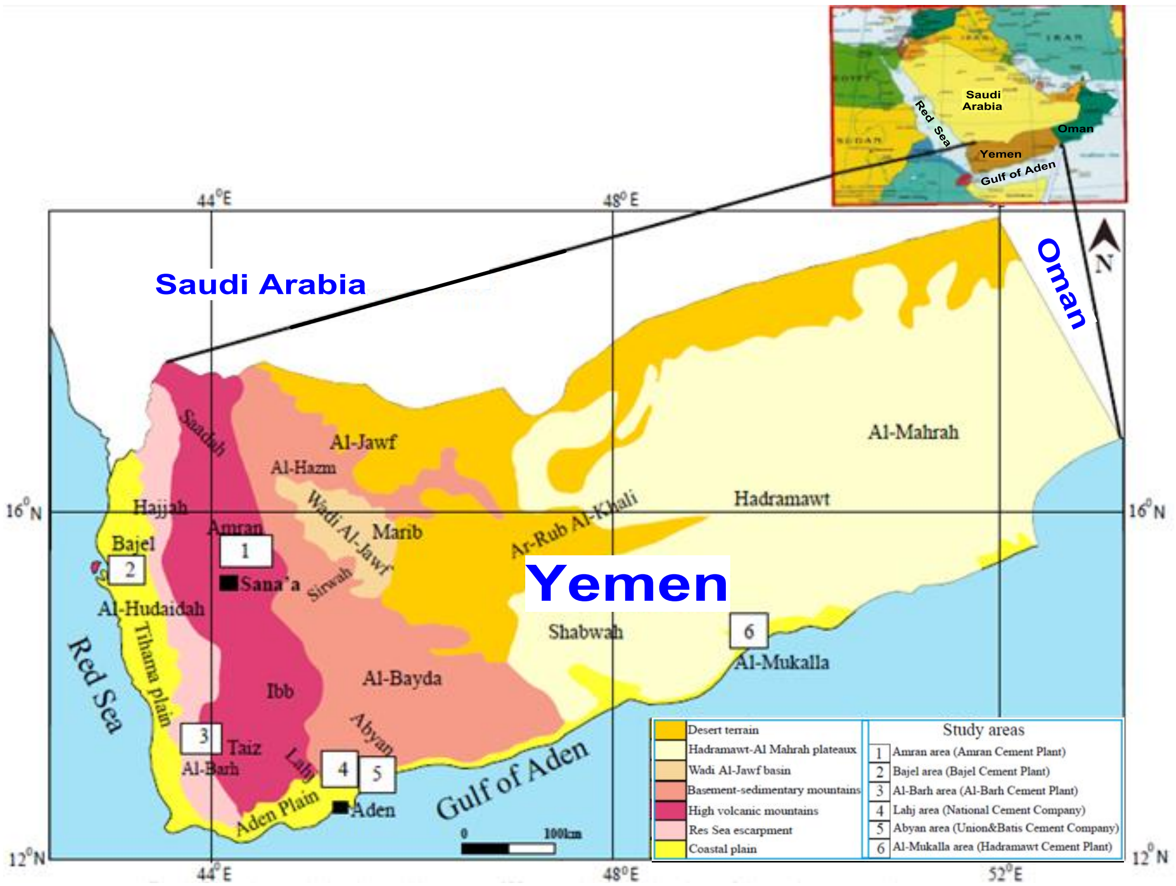

Fig. 1. Location and physiographic maps of Yemen showing the sites of the main cement plants (compiled after El-Anbaawy, 1985 and Al-Khirbash, 2003).

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

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, metamorphic rocks.	Substitutes	–	√	–	√	√	–

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

This study aims are: (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 numbers of recommendations concerning the means of dealing with these complications and hazards as well as the conservation of the natural resources.

Methodology

The study quarry sites are situated in the region lying between longitudes 42°55'- 49°30'E and latitudes 13°00'- 15°10'N. They were grouped into three geographic sectors; the western (A) comprises Amran, Bajel and Al-Barh areas, the southwestern (B) includes Abyan and Lahj and the southern (C) represented by Al- Mukalla. Each of these sectors has its own physiographic and geologic characteristics (Fig. 1, Table 1).

The geological background of the studied quarry sites is based on the information reported in the works conducted by IHI (1980), GEOMINE (1985), Govald (1988), Holtic (2008) and others. These works included mapping of the quarry sites and their vicinities as well as describing the rock successions in bore holes and trenches. The basic data included also topographic maps (1:50,000), geologic maps (1:250,000) and satellite images.

Comprehensive field work was conducted to determine the geologic settings of the six quarries sites and the obtained data were used to construct detailed geologic maps and cross sections. It comprised also sampling and lithologic description of selected representative stratigraphic sections inside the raw materials quarries and in their vicinities. Moreover, the quarrying conditions including the types of opening of the quarry faces were determined and the degrees of slope and stability of the escarpments were measured. The geological complications and geotechnical difficulties that are presently facing or may face in the future the quarry processes were assessed. Furthermore, the geoenvironmental hazards of the quarries and their vicinities 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. Processing images was conducted using ERDAS Imagine (8.5) remote sensing techniques on a personal computer platform. The Geographic Information System (GIS) was developed to produce the maps using Arc GIS (10.1).

Geological Setting

(a) The carbonate quarries

The detailed geological characteristics of the carbonate successions in the studied quarry sites are summarized in Table 2 and the constructed geologic maps and cross sections are shown in Figs. 2 to 7.

In Amran, the carbonate raw materials used in ACP are exploited from two quarries (old and new) in Jabal Al-Merhah. Abu-Zaid et al. (2015) reported that these carbonates belong to the Shuqra and Madbi formations; the former is thicker and more widespread (Fig. 2). 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). 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. 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^o-10^o) and the fold axes are generally aligned parallel or perpendicular to the trends of fault blocks. The latter resulted from normal faults having different directions and scales and forming several grabens and horsts. Oblique or strike-slip faults separate the old and new quarries.

The carbonate succession in Bajel area belongs to the Shuqra and Madbi formations (Fig. 3). 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). 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 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 normal trending NW and NNW and forming grabens and horsts. Step faults and NE and ENE oblique or strike-slip faults represent the most dominant type in the Flaifelah quarry site. Monoclines and synclinal and anticlinal folds as well as basic sills and dykes are common.

The carbonate succession in Al-Barh area (Jabal Al-Awgaa quarries) belongs to the Shuqra and Madbi formations (Fig. 4). 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. Structurally, the carbonate succession constitutes a main horst or ridge which is bounded by major intersecting faults trending NNW and NNE. These faults affect the wings of major synclinal and anticlinal folds the axes of which extend mainly S-N. 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 that is bounded at the fold wings by gently-tilted beds of the Madbi Formation. The limestone ridge in 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 recorded in both the carbonate succession and the Tertiary igneous rocks.

In Abyan area, the carbonate successions belong to the Nayfa Formation and, less commonly, the underlying Madbi and Shuqra formations (Fig. 5). 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). 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. It forms highly dipping monoclinal folds trending WSW-ENE. The scarp slopes of the mountains follow the bedding of the carbonate layers which dip about 300 to the SE. The whole area is affected by faults trending NW, NNW and ENE and their zones are commonly filled with secondary gypsum.

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

Area	Quarry	Rock unit			Lithologic unit	Lithology	Main structural features
Amran	J. Al-Merhah (old & new)	Amran Group	Madbi Fm		Upper-most	Marly and chalky limestone	Several fault blocks, gentle-plunging folds, fractures, 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, Fleiflah		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. 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, karstification caves commonly filled with gypsum.
					Lower	Brecciated limestone	
Lahj	J. Saam		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, karstification

In Lahj area, the carbonate succession belongs to the Shuqra Formation which rests unconformably on the Precambrian basement rocks (Fig. 6). 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).

The carbonate outcrops are dissected by faults having a general NW-SW strike. Noticeable shearing and shifting of rocks in different directions resulted in the creation of fractures along bedding planes trending N to NW and dipping 100-200 NE. Several basaltic and doleritic dykes are recorded.

In Al-Mukalla area, the carbonate raw materials are exploited mainly from the Al-Mukalla quarry which is located to the south of Abdullah Gharib area (El-Eoon). These carbonates belong to the Paleocene Umm er Radhuma Formation (Hadramawt Group) which disconformably overlies the Cretaceous Al-Mukalla Formation (Fig. 7). 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. The chalky limestone commonly contains iron oxide spots and microfossils. The dolomitic limestone is fine-grained, hard, 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. 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. 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.

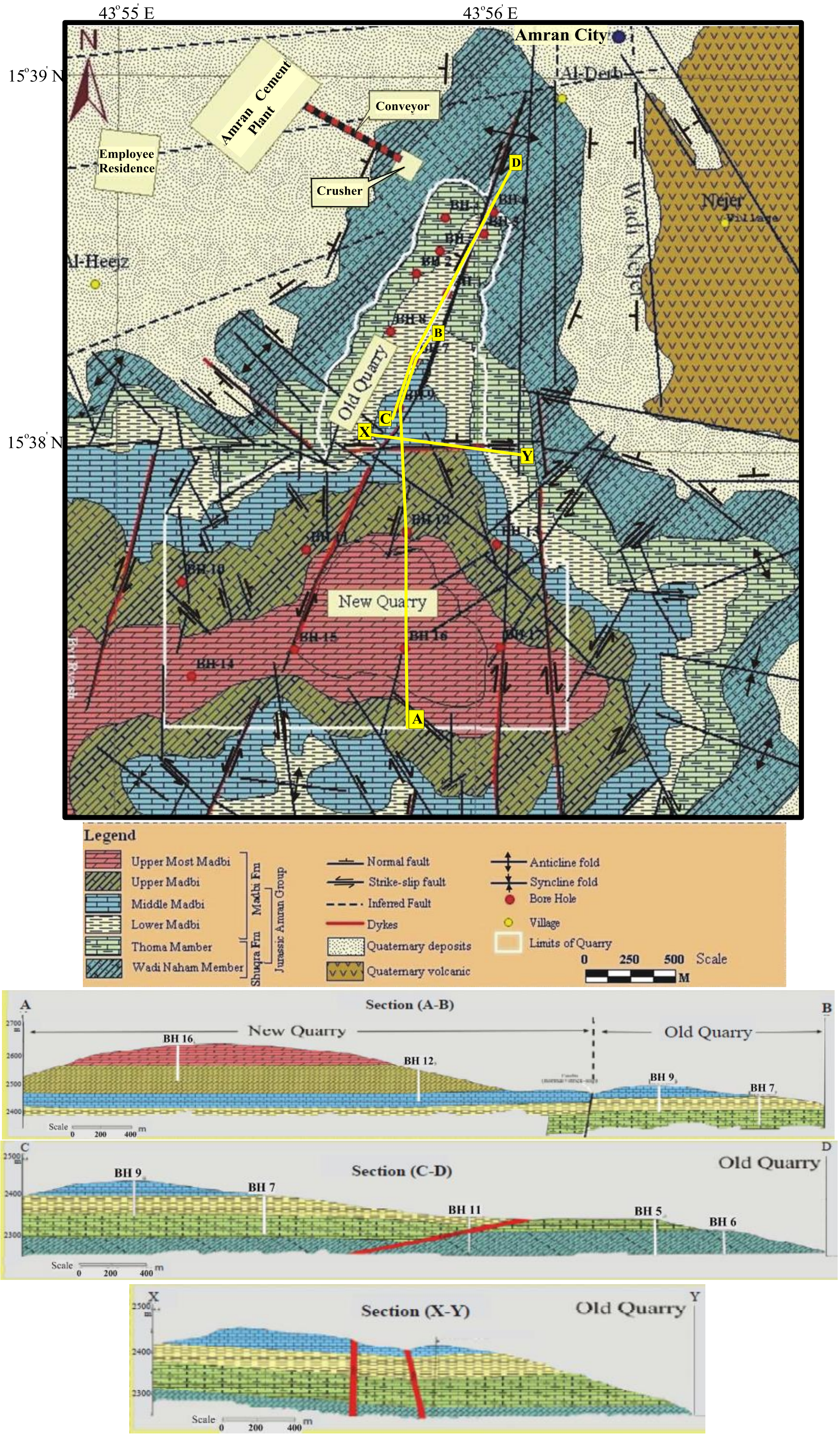

Fig. 2. Detailed geological map of the old and new quarry sites in Amran area and cross-sections from A-B, C-D and X-Y (Al-Anweh, 2010).

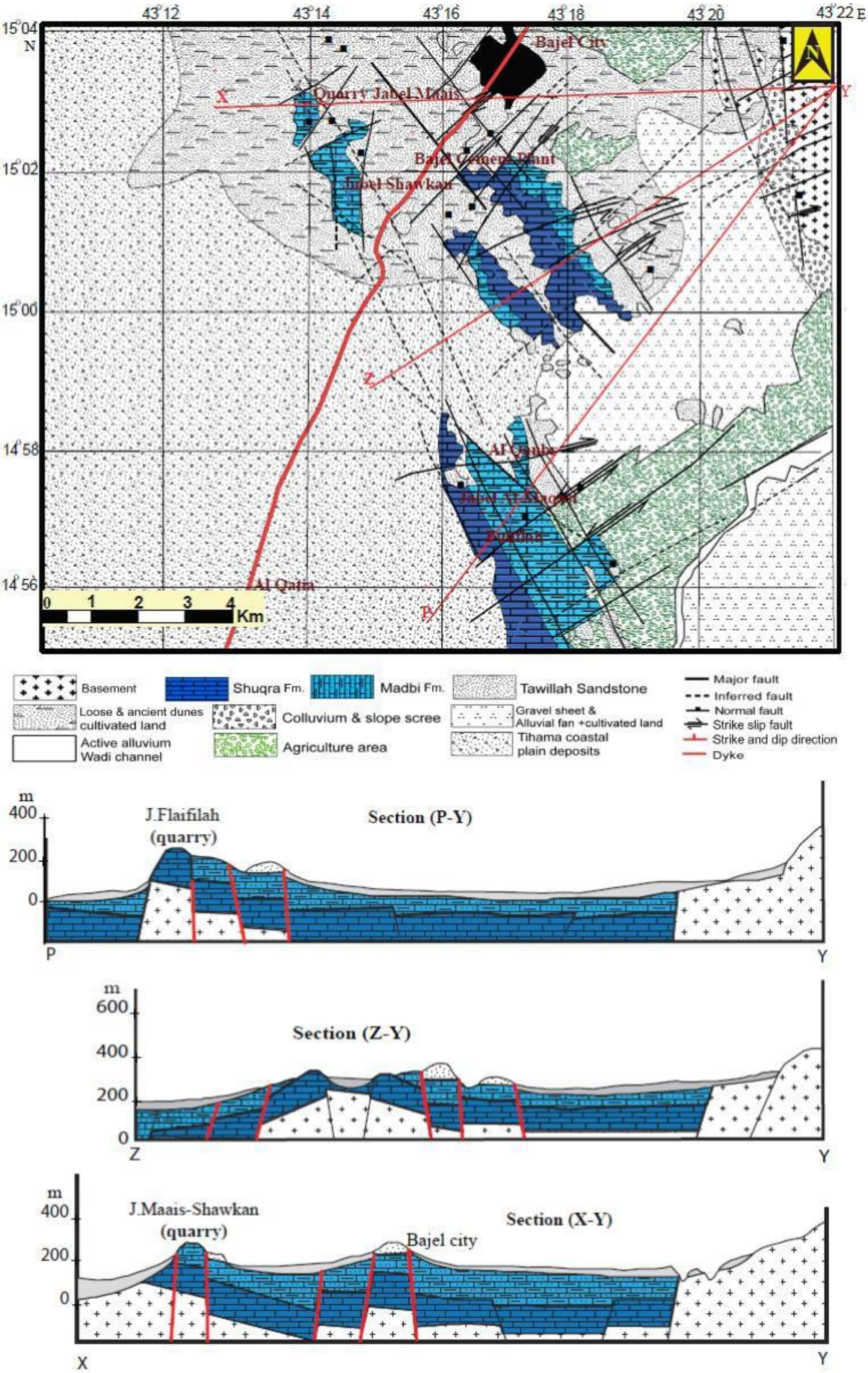

Fig. 3. Detailed geological map of the quarry sites in Bajel area and cross-sections from P-Y, Z-Y and X-Y.

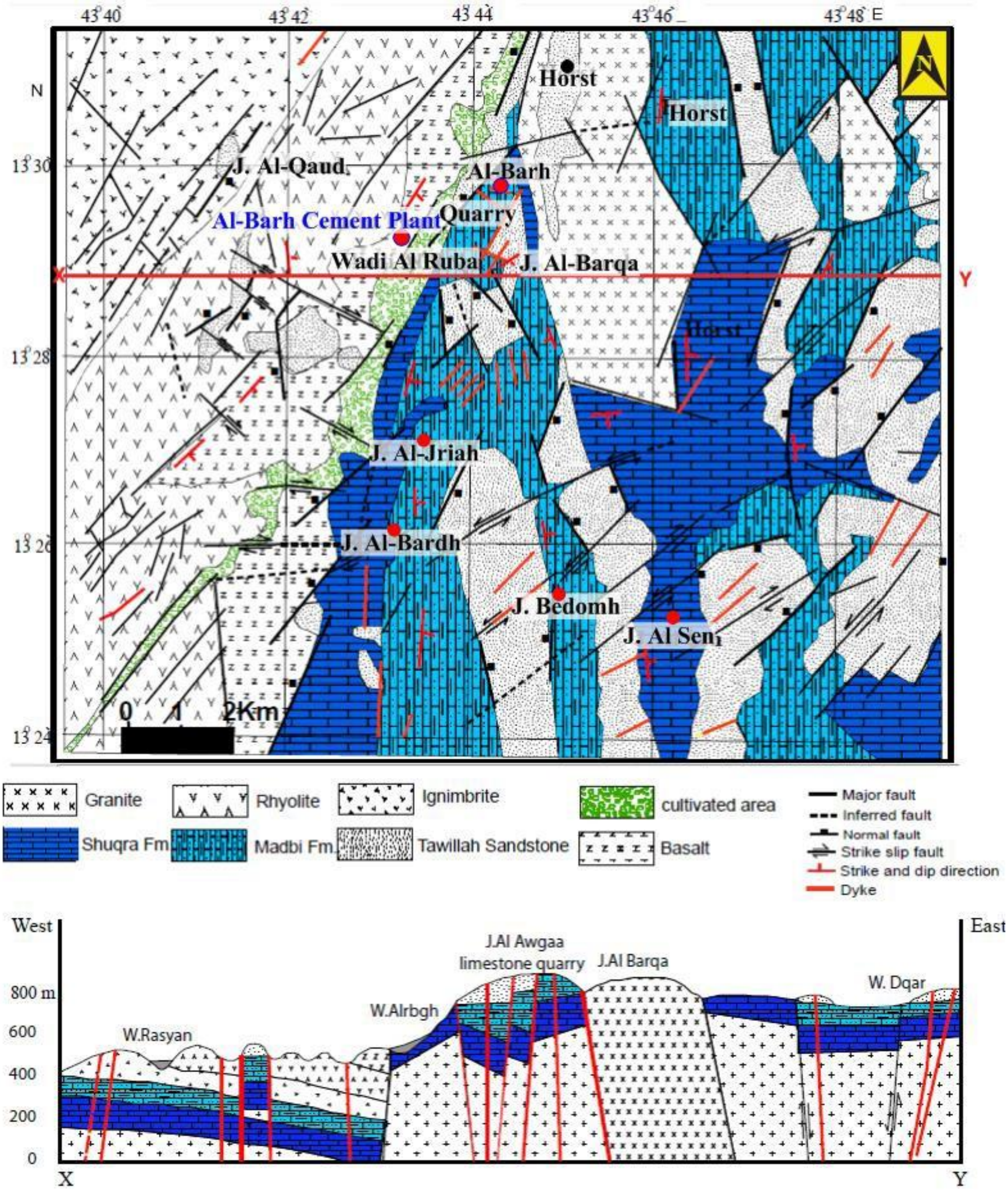

Fig. 4. Detailed geological map of the quarry sites in Al-Barh area and cross-section from X- Y.

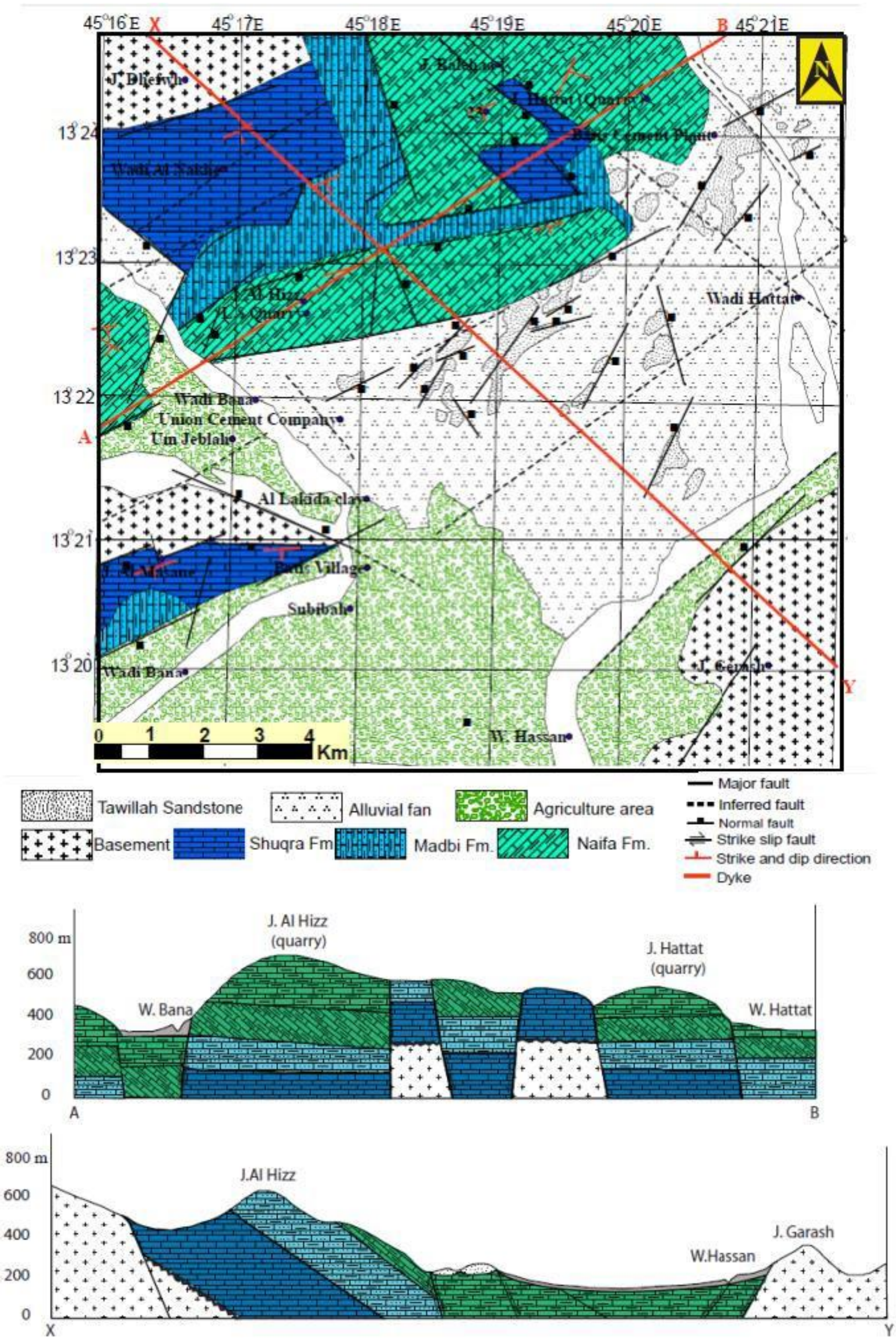

Fig. 5. Detailed geological map of the quarry sites in Abyan area and cross-sections from A-B and X-Y.

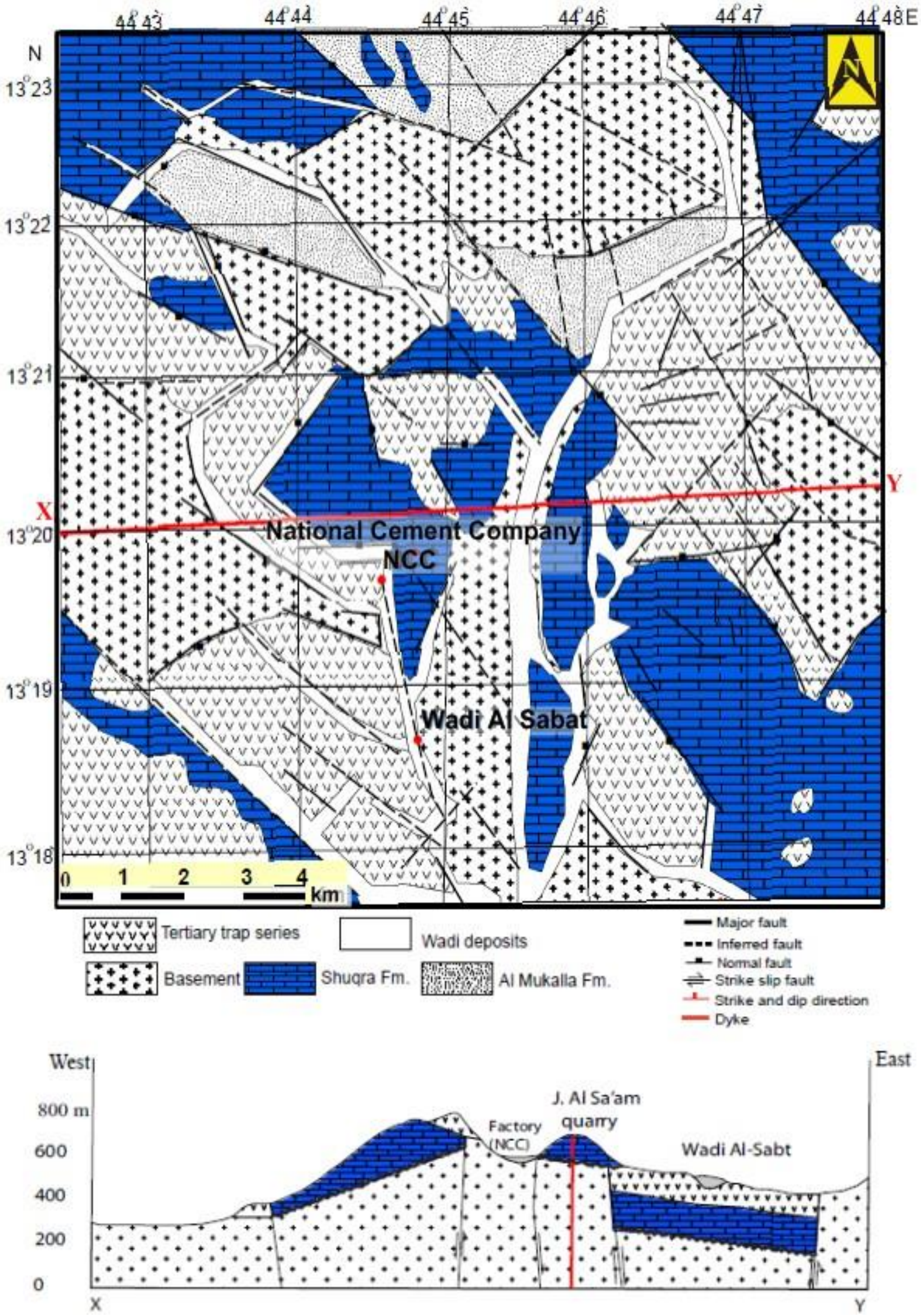

Fig. 6. Detailed geological map of the quarry sites in Lahj area and cross-section from X-Y.

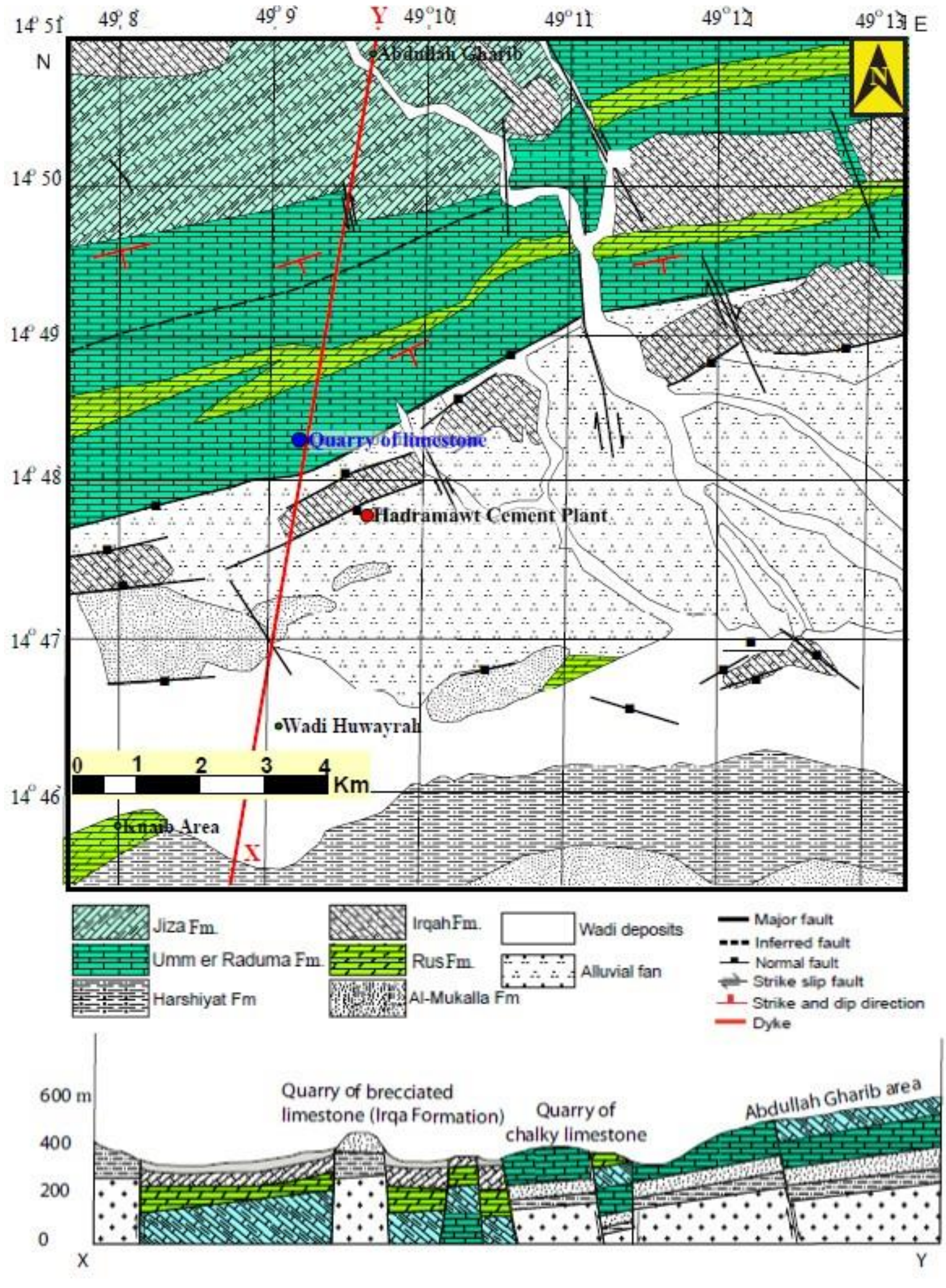

Fig. 7. Detailed geological map of the quarry sites in Al-Mukalla area and cross-section from X-Y.

(b) The sand-clay quarries

The sand-clay raw materials are exploited from the Cretaceous Tawilah sandstone, Al-Mukalla Sandstones the Eocene Rus Formation and Quaternary wadi deposits which are represented mainly by cultivated and/or reclaimed land for agriculture. 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 Bajel area. The quarried outcrops of the Al-Mukalla Sandstone form hillocks within the wadi plain of Abyan Delta.

(c)The gypsum quarries

The gypsum raw materials are exploited from the Jurassic Sab'atayn Formation in Al-Gharass, the Miocene evaporites in Bajel and Al-Barh areas and the Eocene Rus Formation in 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.

(d) 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 Abyan, Lahj and Al-Mukalla areas exploit scoria and volcanic tuff from the Quaternary Aden Volcanic Series in the Shuqra volcanic field. 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 other hand, the basement rocks in 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.

Quarrying Methods and Conditions

(a) The carbonate quarries

The carbonate raw materials in all the studied sites are quarried applying the open method (step-quarry operation) or the 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 makes the quarry under control during all steps of excavation. Technological development of quarrying systems of carbonate raw materials involved opening of the quarry top-down from the top of a hill (block) where the drilling levels and bench heights are designed first (Fig. 8a).

(b) 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 applying 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 height (Fig. 8b). Commonly, the quality distribution pattern of these deposits demands vertical cutting of the bench using 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.

(c) The gypsum quarries

The gypsum raw materials in Kulagah, Thoma, Salif, Al-Mahfed and Kuaib quarries are commonly quarried applying the single-bench open mining by manual use of pneumatic hammers, blasting and excavation using wheel loaders (Fig. 8c).

(d) The gypsum quarries

The gypsum raw materials in Kulagah, Thoma, Salif, Al-Mahfed and Kuaib quarries are commonly quarried applying the single-bench open mining by manual use of pneumatic hammers, blasting and excavation using wheel loaders (Fig. 8c).

(e) The gypsum quarries

The gypsum raw materials in Kulagah, Thoma, Salif, Al-Mahfed and Kuaib quarries are commonly quarried applying the single-bench open mining by manual use of pneumatic hammers, blasting and excavation using wheel loaders (Fig. 8c).

(f) 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 at a small scale. All materials are exploited applying open pit surface quarrying by manual use of pneumatic hammers and hand tools (Fig. 8d). Blasting is exercised from time to time in order to fractionize the rocks.

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, thickness and quality; (v) presence of igneous sills and dykes some of which are intensively weathered; and (iv) abundance of karstification features (mainly dissolution cavities).

Some of the cement raw materials exist in mountains having high elevations, steep slopes and/or rugged topography with profound ridges which results in difficult quarrying conditions (Fig. 9a). For example, the Sa'am limestone succession (~60 m thick) in Lahj area overlies a hill of granitic basement rocks which is about 590 m (a.s.l.) (Fig. 9b). Also, the Batis limestone deposits in Al-Hizz quarry (Abyan area) are confined to highlands having the form of ridges with steep slopes (30^{o}-32^{o}) accompanied with high dip angles (80^{o}-85^{o}) of the strata (Fig. 9c). A similar situation exists in Bajel where the steep slopes (15^{o}-30^{o}) of some carbonate plateaux have negative impact on the quarrying conditions.

Tectonic tilting of beds and intensive faulting and fracturing represent a major problem in quarrying carbonates and gypsum in their sites. Also, the presence of sills and dykes may cause rapid structural changes. In Al-Mahfed and Kuaib gypsum quarries at Al-Mukalla area, the beds have high angles of dip (about 20^{o}) causing great difficulties in quarrying. The carbonate beds in Jabal Sa'am (Lahj area) have smaller dip angles (10^{o} and 20^{o}) but are very steep in places due to structural deformation caused by intensive faulting. In Bajel quarry site, the normal faults and associated open extension fractures (Fig. 9d) are active structures which accelerate landsliding on the plateau slopes. Also, the presence of numerous intersecting fractures and joints facilitates the mechanical and chemical weathering of rocks in the majority of carbonate quarry sites particularly at Lahj (Fig. 9b) and Abyan (Fig. 9e).

Heterogeneity in bed thickness and lithologic composition is very common in all the studied quarries especially those of carbonate raw materials. This heterogeneity resulted in marked differences in the intensity, type and direction of joints between the limestone beds and the calcareous shale and marl interbeds (Fig. 9f) as well as between the basement rocks and the overlying tilted limestone strata (Fig. 9b). In 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, intensity of fracturing resulted in marked variations in the extent of weathering which caused the development of rugged topography.

The difficulties of quarrying particularly in also the 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, the intensity of the relatively recent tectonic line. These difficulties become more significant with the increase in 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 (Fig. 9g). 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 (Fig. 9h). The developed karstification and the presence of various heterogeneous filling materials led to irregularity in the mountain slopes and heterogeneity in the raw materials composition.

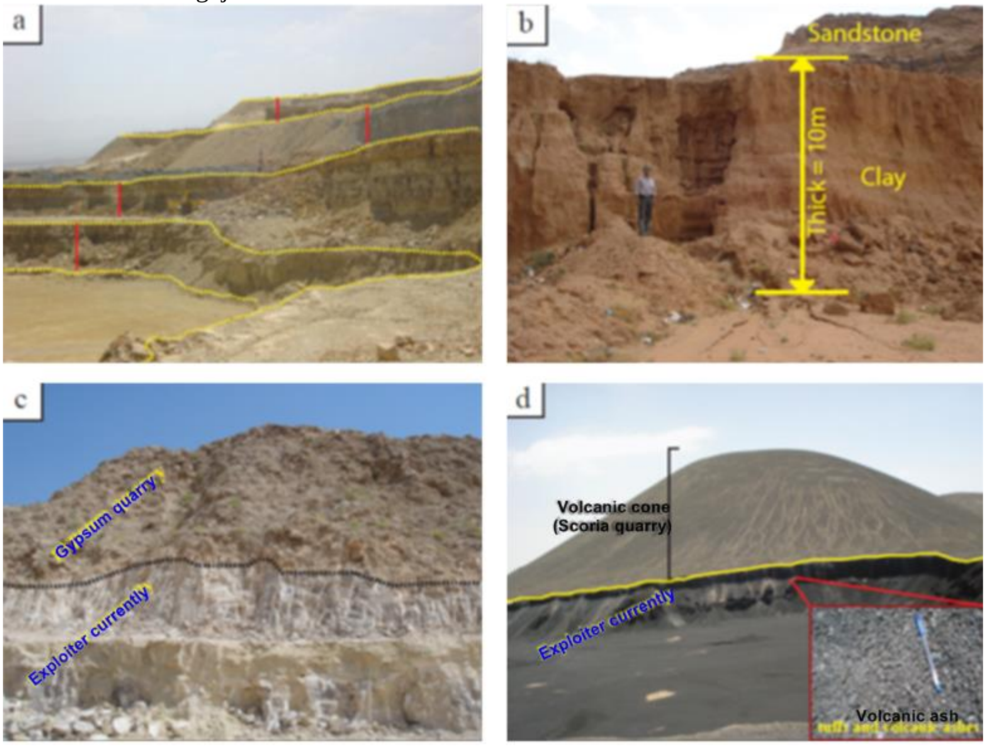

Fig. 8. Field photographs showing the applied methods of quarrying the cement raw materials: (a) Proper exploitation of a carbonate succession. The quarry was opened from the hill top after designing bench heights (Amran area), (b) Open pit quarrying in a succession of Quaternary soft soil clay overlain 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).

Environmental Hazards

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

(a) Natural geological hazards

Mass-wasting in the various quarry sites results mainly from land and overburden sliding, toppling, soil failure and rock fall. Landsliding is governed by a complex physical system which is controlled by factors such as slope morphometry (e.g., angle of slope), 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 represent the most effective structural elements in slope instability and landsliding. According to the orientation of the slope faces, the major structural trends affect variably the stability of slope and landsliding in different parts of the quarry site. In the highly-fragmented and weakly-cemented rocks, under-cuttings 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, 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 resulted in the formation of stepped scarps including flat tops, straight slopes and vertical free faces. In some quarrying sites, the mass wasting particularly landsliding and toppling was triggered by the increase in water pressure on joints and micro-fractures and/or by natural or artificial seismic activity. Moreover, the use of water during drilling for explosion facilitated landsliding and rock fall in some quarries.

(b) 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 accumulation at the toe of high-steep slopes that are associated with falling of rock blocks during quarrying (Fig. 10a); (iii) soil failure, rock fall and sliding of the clastic overburden particularly in gypsum quarries which are characterized by lithologic heterogeneity (Fig. 10b); (iv) change in topography of the overburden surfaces on mountain slopes due to quarrying using improper methods which led to instability hazards (Fig. 10c); (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 (Fig. 10d); (vi) emission of noise that accompany quarrying processes especially explosion; (vii) accidental spillage and leakage of operational water during quarrying which led to landsliding and/or flooding into the neighboring farm lands and residential areas (Fig. 10e); and (viii) accidental events that resulted from collision or getting stuck between the quarry tools and equipments 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 (Fig. 10f).

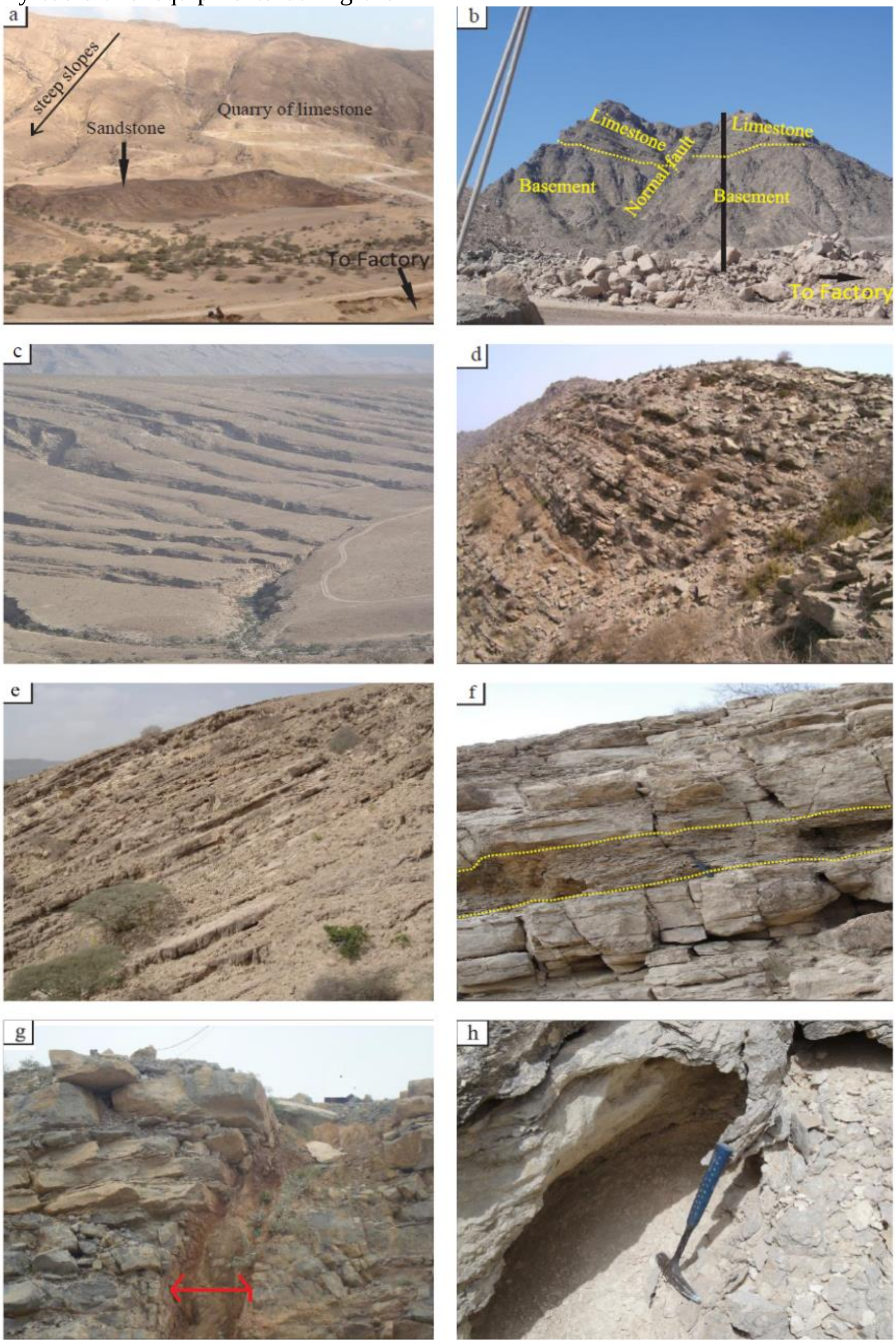

Fig. 9. Field photographs showing some geological complications in the studied quarry sites: (a) The high elevation, steep slopes, rugged relief and complex topography in Al-Hizz carbonate quarry (Union Cement Company), (b) Rugged topography of a high hill made up of basement rock by capped limestone in Jabal Sa'am (National Cement Company). Structural deformation resulted from intense faulting, (c) Profound ridges and rugged topography in Al-Hizz carbonate quarry (Hadramawt Cement Plant), (d) Normal faults associated with open extension fractures in Bajel carbonate quarry (Bajel Cement Plant), (e) Extensive fractures and joints in highly-tilted beds in the Jabal Al-Hizz carbonate quarry (Union Cement Company), (f) Difference in the intensity of jointing between limestone and marl interbedded in Al-Hizz quarry (Union Cement Company), (g) An intensively weathered volcanic dyke in the limestone succession of Al-Barh carbonate quarry (Al-Barh Cement Plant), (h) Solution cavities in the Nayfa limestone in Jabal Al-Hizz carbonate quarry (Union Cement Company).

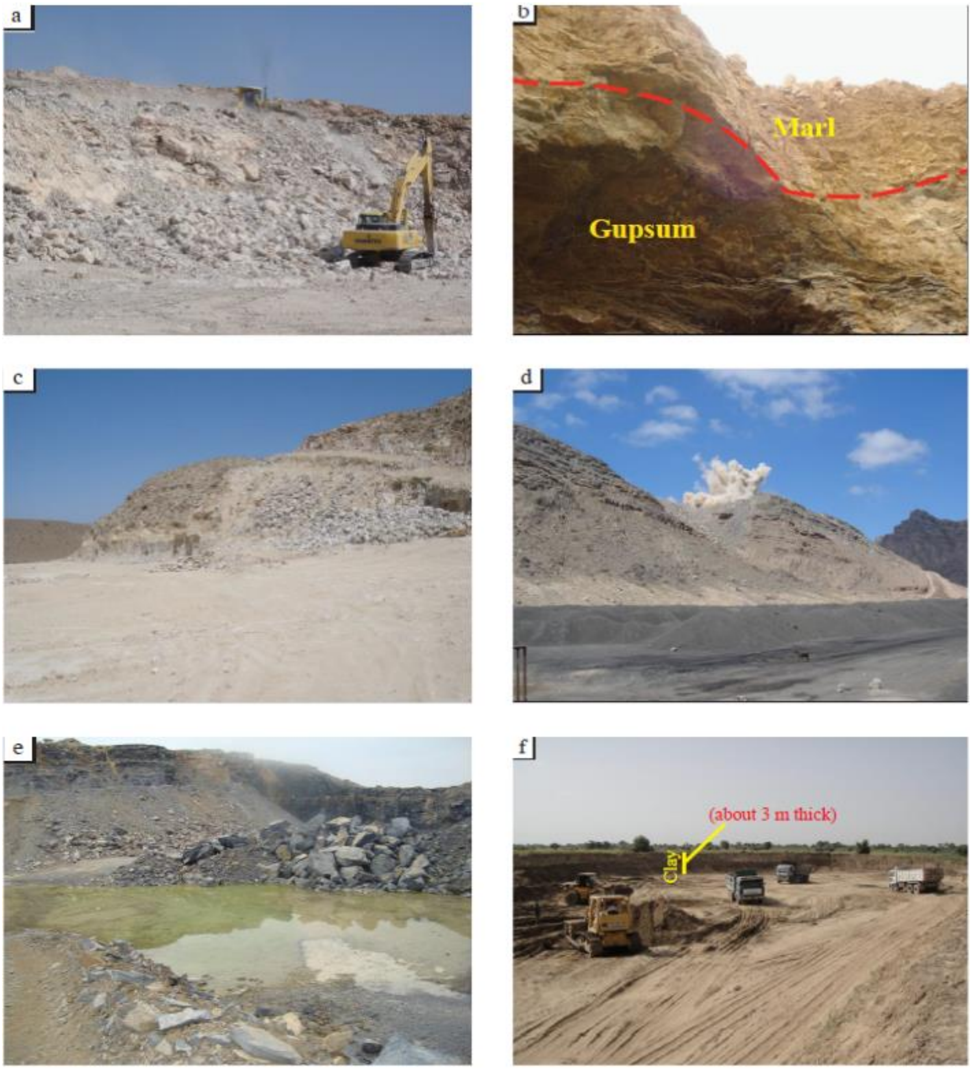

Fig. 10. Field photographs showing some geoenvironmental hazards in the studied quarry sites: (a) Rock fall and sliding of the clastic overburden in a carbonate quarry in Al-Mukalla area (Hadramawt Cement Plant), (b) Gypsum beds intercalated with and overlain by thin marl beds in the gypsum quarry at Amran area (Amran Cement Plant), (c) Steep slopes developed as a result of falling of separate rock blocks in Al-Mukalla area (Hadramawt Cement Plant), (d) Dust emissions accompanying the explosion and other quarrying operations (National Cement Company), (e) Accidental spillage and leakage of operational water during quarrying (Al-Barh Cement Plant), (f) Excavation of agricultural soil in Al-Lakida clay quarry (Union Cement Company).

Conclusions and Recommendations

The presently exploited quarries of cement raw materials in Yemen have several problems related to geological complications, environmental hazards and improper conservation of the 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 several 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 in 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 inventory and hazard maps which are essential for designing the planning system of quarrying operations; (vi) learning 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 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) avoiding raw material wasting in the quarry site by pounding proper through safe working conditions; (iii) preparing and implementing a sustainable plan of recycling both the fresh water supplied to the quarry and plant for drinking and cooling purposes and the recycling water 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) and the basement rocks (Abyan and Lahj); (v) avoiding the accumulation of water volumes on the quarry terraces; (vi) applying safety measures during transportation of the raw materials; and (vii) inspecting and maintaining all the equipments used in quarrying operation; (viii) prospecting for additional water resources. These 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 (Batis-Abyan) and Hattat areas.

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