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Geotechnical Integrated Approach to evaluate the karst hazard potentiality in the Qatar Coastal Eocene carbonate bedrocks

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ABSTRACT **: The Eocene carbonate bedrocks in the central-eastern coast of Qatar are characterized by heterogeneities in geotechnical setting due to the wide spreading of subsurface karst cavities in different stratigraphic levels at all scales. Therefore, the present study attempts to construct a geological hazard potential map to quantify these karst cavities using the integration of different techniques, which are shallow seismic (MASW) survey and borehole coring. However, it is indicated that the interpretation of geotechnical properties of the bedrocks is probably more difficult since karstification processes often modify the original compaction and strength of the rocks and consequently modify the average of seismic velocity pattern leading to miss-interpretation. To improve the interpretation certainty an applicable depth seismic wave velocity model was proposed. This model depends on the correlation and integration of the velocity classes revealed from the MASW profiles with the geological significance of nearby geotechnical verification boreholes.**
Depending on the borehole correlation charts models three representative geological cross-sections were delineated to demonstrate the tectonics and sedimentation controls dissolution. The petrographic rock types and the hydro structural condition seem to be the main causative factors controlling the karstification potentiality and consequently controlling the engineering rock quality. As revealed from the spatial integration of all contributing factors, most of the eastern (Lusail) and south eastern (Al-Wakrah) sectors are prone to serious subsurface karst hazards. In this respect, it is strongly recommended to provide full integrated geotechnical data prior to any new developing project in these shoreline sectors.

KEYWORDS: ***Eocene carbonate bedrocks of Qatar, Validity of MASW interpretation, core characterization, karst morphology, karst cavities delineation.***

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I. INTRODUCTION

The state of Qatar has an elliptical shape province and lies at the eastern edge of the Saudi Arabian land mass and constitutes a peninsula of 10,000 km2 extending some 180 Km into the Arabian gulf between latitudes 24o 30` and 26o 10` and longitude 51o 00` and 51o 30`. The land surface of Qatar is characterized by low relief topography with a maximum height of 103m above sea level and the major level of the country is below 40m above sea level (Figure 1a).

The desert-coastal geoenvironmental conditions of the Qatar Peninsula including the study area (central eastern coastal plain of Qatar) create some geological hazards. The most effective of them is karst hazards. Although, Qatar is considered as a mature karst terrain few investigations have been conducted on karst geomorphology, development and hazard potentiality. The most important investigations are those of Cavalier (1970), Embabi and Ali

(1990), Sadiq and Nasir (2002), Duggan (2014), and Orndroff et al. (2017). Rivers et al., (2018 & 2019) who created a fault and erosion model in the western part of Qatar.agency, Egypt; January 2009, is about 600 ton/annually in agricultural and pests control in Egyptian aquatic environment [6].

The coastal bedrocks in the study area, like those in Qatar, are dominated by surface and near surface Eocene carbonates and evaporites beds where they suffer from problem of Karstification. These bedrocks were subjected to groundwater solution acting during wet paleoclimatic condition creating wide spreading karst phenomena (e.g. sinkholes, caves and karst depressions).

Commonly, the karsted bedrocks dissolution cause hazards for construction, potentially impacting the load-bearing capacity of the bedrock in the promised urban areas and consequently creates obstacles to the Qatar development plans. Furthermore, karst hazards are occasionally related to currently leakage of urbanization water of dewatering, lowering and rising of groundwater levels which may cause in land subsidence and groundwater contamination. Land subsidence and subsequent ground fissures and foundation instability that associated with the karst depressions are considered as the surface expression of subsurface collapse structure. This hazardous karst situation could damage human properties, building and infrastructure particularly near the eastern shoreline where the study area is located.

The karst features and their impacts on the Qatar carbonate bedrocks pose and potential need to be considered for land use planning (Orndorff et al., 2017). Therefore, the present study gives an overview of the karst hazards in Qatar and tries to develop detailed subsurface geohazard profile in the study area using integration of geological, geophysical survey and geotechnical boreholes data. Accordingly; The aim of this study is 1) to use the available field data collected from boreholes samples, geological data and geophysical profiles to evaluate the karst hazards within the eastern coastal part of Qatar; 2) to determine the geophysical limitations and root causes that might lead to a false interpretation of the geophysical data; and 3) to prepare a geoengineering hazardous map based on interpretation and integration of the results from the study which could predict the Karst Hazardous to be taken into consideration for the future construction within Qatar.

II. LOCATION AND GEOLOGICAL SETTING OF THE STUDY AREA

The study area is located between latitudes 25º 00`& 25º 45` and Longitude 51º16` & 51º 40` (Fig. 1b). The area is accessible through the main asphaltic roads (highway) that are branched from Doha (the capital of Qatar) to the north (Madinat Al Shamal) and the west (umm Ghwallina and Abu Nakhla) and to the south (Umm Said). Large numbers of studied wells were drilled along the east central part of the peninsula and along the eastern coastal area extending from Al Khor in the north to Wakrah at the south to evaluate a soil investigation study and to determine the geotechnical properties of the subsurface strata in the area of study. The study wells were drilled in approximately one line starting from Abu Nakhla – South to Al Khor – North (Fig. 1a) cutting Dukhan Road near Umm Al Afaei, Al Mazrooa Road near Umm Salal Ali and Al Shamal Road near Al Khor with approximately 60Km distance. Topographically, the study area is almost flat with small difference in attitude from place to place with a minimum of 18.7m and a maximum of 39.5m above ground level. The ground surface is covered by Quaternary deposits ranging between 0.50 and 1.50m below ground surface consists of sandy, silty and clayey material with an amount of limestone gravels and crystalline gypsum. The study area is divided into five major sectors, 1) the Northern Sector (N), 2) the Middle Sector (M); 3) the Eastern Sector (E); 4) the Southern sector (S); and 5) the South Eastern Sector (SE) (Fig. 1a and b).

Regionally; The sedimentary succession has been subjected to a gentle compressional tectonic activity, that leads to the formation of the Qatar Arch Domal anticline structure accompanied by erosion processes have determined the topography of the peninsula. This broad anticline has a north-south axis and is gently dipping towards the Qatar peninsula is a part of the Arabian Gulf Basin and considered as stable Arabian interior platform, within this basin, gentle tilting, subsidence and sedimentation was continuous since the Cambrian time creating a thick sedimentary succession, composed mainly of carbonate and evaporite sediments (Cavellier et al., 1970; Fourniadis, 2010) east and west. The study area is situated within the eastern basin of the anticline stretching from the coastal area to the east and reaching to the west towards the anticline axis (Fig. 1a).

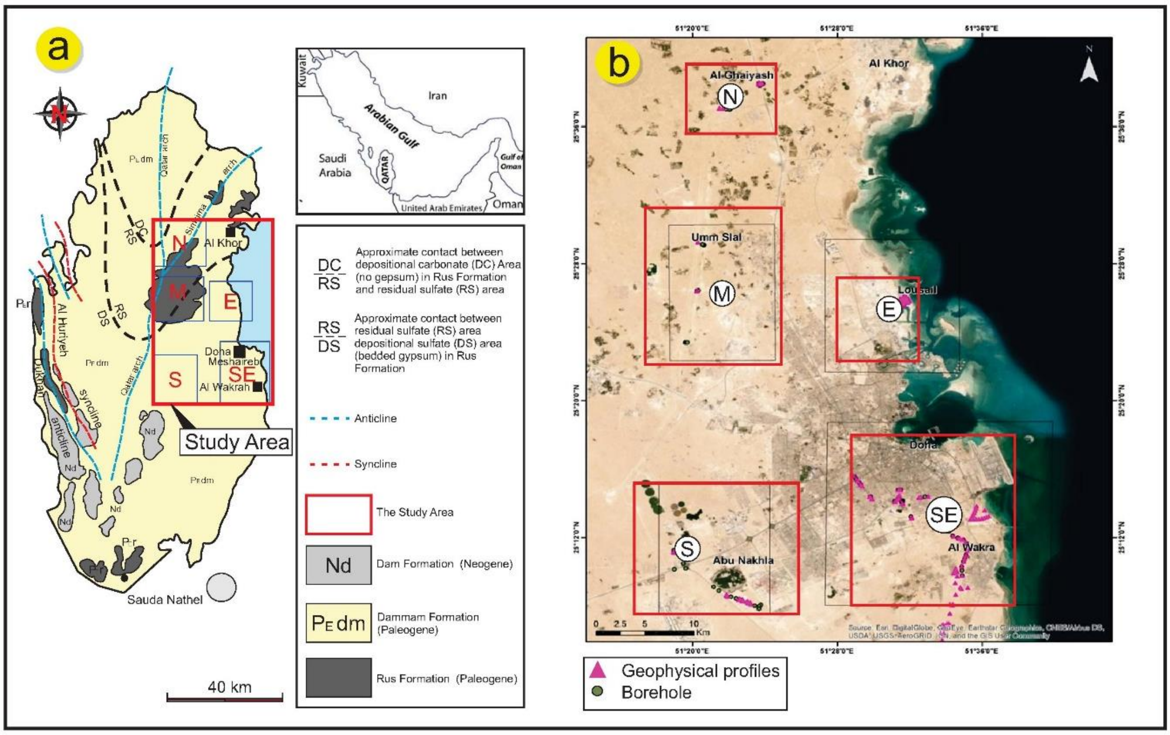

Fig.1.a) Geological map of Qatar showing the main exposed rock units and the boundary of the five studied areas (sectors), **b)** satellite image showing the study area and distribution of the study sectors (N, M, E, S & SE) along the area.

Qatar sedimentary cover is mainly composed of carbonate rocks with different composition, varied from limestone, dolomite, to gypsum. The penetrated sedimentary succession is composed mainly of Tertiary limestones interbedded by marls, clays and shales covered by Quaternary deposits and recent superficial sediments (Table 1).

In this respect, the area under study is located mainly within the southern division (DS) and to a little extent to the central division (RS) that were suggested by Eccleston etal. (1981), Sadiq and Nasir (2002), and Duggan (2014) for the genetic classification of karst depressions as shown in Figure 1a.

Accordingly, the depressions within the northern sector are associated with residual sulphate (residual gypsum) while those of rest sectors are deep circular depressions (up to 20m depth) which are often more crater-like in appearance. Furthermore; many of the depressions of the study area have been infilled with aeolian sand with some natural scattered vegetation.

Table 1. Main lithologic units in Qatar; modified after Cavelier (1970)

Age		Formation	Member with Thickness (m)	Lithology
Quaternary	Holocene	-	-	Sand dunes, beach sand & wadi deposits
	Pleistocene	-	-	Beach rocks, fixed dune, depression with calcareous deposits
Tertiary	Pliocene - Miocene	Hofuf	10-12m	Gravel and Sand
		Dam	Al Nakhash ~50m	Limestone interbedded with marl & clay
			a)Salwa (Al-Kharrara) ~30m	Mudtone, claystone interclated with fossiliferous marl
	Oligocene – Late Eocene	Centeral arch (Qatari dome uplift		Dolomitization processes
	Early-middle Eocene	Dammam	e)Abarug* 2-10m	Dolomitic Chalky limestone
			d)Simsima* (Umm Bab) 10-30m	Very variable chalky-dolomitic limestones with voids
			c)Dukhan* 0-1m	Compacted Fossiliferous chalky limestone
			b)Midra* 0-10m	Shale to laminated claysotne interclated with marl & limestone
			a)Fahahil* 0-1m	Crystalline fossiliferous limestone
	Early Eocene	Rus	b)Al-Khor* 10-20m	Chalky limestones with vesicular dolomite
			a)Traina* 10-100m	Anhydrite/Gypsum with gypsiferous mudstone interclations
	Paleocene – Early Eocene	Umm er Radhuma	Mainly subsurface 300-500m	Limestone interbedded with dolomitic marly limestone

* Members which are represented in the study boreholes ------- Unconformity surfaces

III. MATERIAL AND METHODS

Different materials were used and developed within this study to help prepare a complete image of the study area, data analysis and interpretation. Satellite images were used and the study area was potted on it to be used as a base map for the study. The area was divided to five different study sectors based on the lateral and vertical distribution of rock units to help evaluating a comparison study. Several field visits were performed for visual interpretation, sample collection, and carried out the geological and hydrological studies to able to prepare a simplified geological base map for the area. Some boreholes were drilled, core samples were collected, preserved and was sent to storage area for core description and visual examination. After completing the visual examination, a number of samples were selected to be tested, examined and to be studied based on their distribution along the study sectors and the encountered rock units as well. Geoengineering parameters were measured and tests were carried out on the selected samples for engineering evaluation. The rock quality designation (RQD) was measured for the core samples collected along the study boreholes to evaluate the fracture intensity and effect of karsts along the area. The unconfined compressive strength test was carried out in laboratory to integrate the rock strength and effect of rock strength on the shear wave velocities and karst features. Approximately thirty-two subsurface geophysical profiles using Multi Channel Analysis of Surface Waves (MASW) technique were prepared, and layer boundary and karst hazardous were developed and plotted on the profiles to help in data interpretation and analysis. Eight most represented for the study purpose were chosen in the current paper to be representative for the area. Petrographic thin sections were prepared from the collected samples and well-studied to evaluate the petrographic rock type, microfacies, and effect of different rock type on the karst features in addition to effect of rock type on shear wave velocities. X-ray diffraction (XRD) was performed on selected samples for clay minerals and bulk samples study. These analyses help in the study of dolomitization and dedolomitization processes and identification of clay minerals. Finally; a desktop study was carried out for the collected, field data, geological, geotechnical and geophysical data for the conclusion and recommendation.

IV. RESULTS AND DISCUSSION

Field Observation and Geological Map

Three lithological units can be recognized in the simplified geological map (Fig. 2a), these from base to top are:

- Khor Member (Ras Formation, Lower Eocene)
- Simsima (Umm Bab) Member (Dammam Formation, Middle Eocene)
- Quaternary deposits

The Khor Member (Rus Formation) forms a restricted exposures of the study area, while the majority of the area is covered by the Simsima outcrops (Fig. 2a). The Khor Member outcrop occurs to the northwest of the map as whitish or yellowish chalky dolomitic fossiliferous limestone occasionally intercalated with thin beds of greenish to brownish attapulgitic clays. Commonly, the member is unconformably underlies thin beds of Simsima particularly upon or near the central and Simsima arch region where erosion has removed considerable materials over the top of the Rus Formation forming disconformity contact with Dammam Formation (Table 1).

The outcrops of the Simsima Member at northern and middle sectors, particularly near the arches region, are represented by its thin upper unit where its lower unit was eroded. This unit consists mainly of 5m in average of highly karstified dolomitic limestone with chert nodes. The Lower unit of Simsima Member consisting of chalky dolomitic limestone with numerous karstic features, covers the majority of southern, eastern and south eastern sectors (Fig. 2).

The abrupt contact between the exposures of the two members in the geological map (Fig. 2) is coincided with the detected inferred fault in which the downthrown side occupy by the south eastern block of the Simsima limestone exposure. Furthermore, the approximate contact between residual sulphate (RS) area and depositional sulphate (DS) area (bedded Gypsum) in Rus Formation (Eccleston etal., 1981) is located closed to the fault zone and taking its trend (NE-SW or NNE-SSW) as shown in the geological map (Fig.2). Based on this observation it is suggested that the distribution of RS and DS areas that proposed by Eccleston etal (1981) seems to be structurally controlled rather than deposition and dissolution of Rus evaporites (Traina Member).

The eastern margin of the study area is covered by shoreline Quaternary sediments which are mainly composed of terrestrial mixed with marine components (Fig 2a). These Quaternary sediments are distributed upon the coastal (shoreline) geomorphological landforms (e.g. inlets, islands, reefs, capes, bays and extensive field of sabkha or saline coastal playas). The spatial distribution of these landforms suggests the great role of tectonics in shaping the coastal topography.

The study area includes several types of karst features (e.g. Cavities, Caves, sinkholes and depressions). The majority of these features have been developed through chemical weathering (e.g. dissolution) of carbonate bedrocks by surface water or underground water penetration along fractures and joints.

Two large sinkholes are recorded within Al Wakrah namely; Hamam and Duhail sinkholes). The wall rocks of these sinkholes are highly jointed and fractured dolomitic Limestone of Simsima Member. It is observed that Hamam Sinkhole is the only one containing sea water along the major fractures and inferred faults at a depth of about 16m. On the other side, The Duhail Sinkhole is considered as transitional to becoming a depression, as indicated by the presence of a collapsed roof in its center at depth of about 4m..

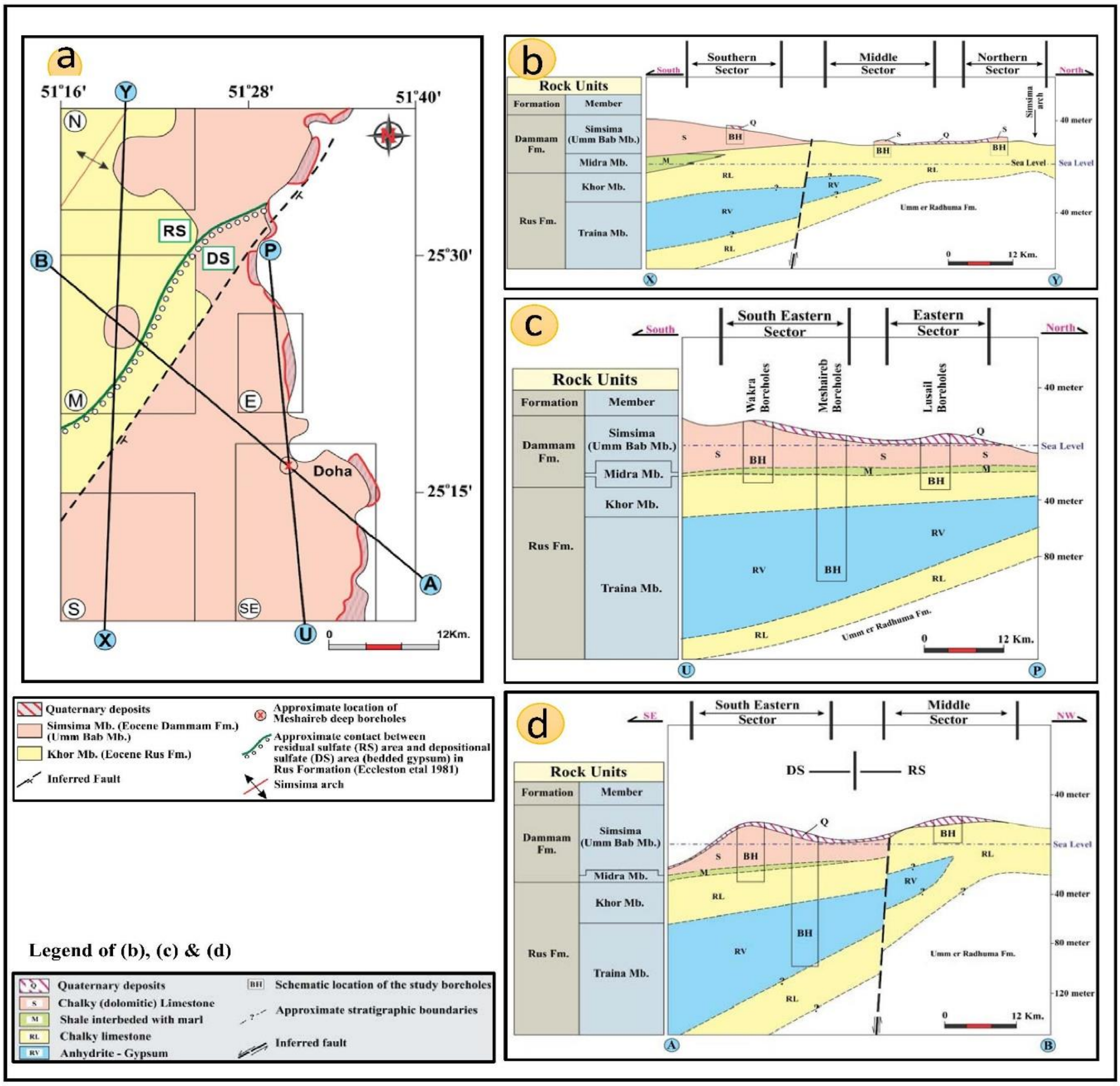

Fig.2. Simplified geological map of the study area and stratigraphic cross-sections along the study area**.**

Boreholes Correlation Chart Models

Based on the constructed simplified map (Fig. 2a) and correlation charts of boreholes along the study area sectors (N, M, E, S & SE), Three schematic cross sections were demonstrated to illustrate the boreholes lithological variation and the effect of faults along the study area (2b, 2c & 2d).

The X-Y section extends from North to South crossing the Northern Sector, Middle Sector and Southern Sector (Fig. 2b). U-P section extends in the coastal area form Al Khor in the North to Wakrah in the South and covers the Eastern sector and the South Eastern sector (Fig. 2c). A-B section extends E-W direction and cross from Doha City and Meshaireb area to the Middle Sector in the West (Fig. 2d).

The represented data from the geological map and the studied cross-sections have revealed some observations as follows:-

1. The relief pattern of the study area seems to be irrespective of its structure system where it is not necessarily to find the downthrown sides of the faults have low relief.
2. The apparent wide variation in distribution and thickness of the Rus evaporites (Traina Member) may be due to their tectono-sedimentation modes and consequence erosional processes rather than dissolution controls. Therefore, the presence or absence of the Midra Shale has no influence on the evaporites dissolution potentiality.
3. Contrasted lithological changes between the upthrown side of the inferred NE-SW fault which mainly occupies the northern and middle sectors, and the downthrown side of the fault that occupies the southern, eastern and south eastern sectors are demonstrated in the geological map (Fig. 2a) and the cross sections (Figs. 2b, 2c & 2d).
   a) The upthrown side sectors are located near The Simsima Arch. The Simsima Limestone in this side is thin where erosion has removed most of surface carbonate material particularly near the Simsima Arch in the northwest corner of the study area (Fig. 2a). The beds of the Khor Member are tilted towards the southeast (almost perpendicular to the Arch. They constitute the surface and near-surface bedrocks which are disconformable overlying abruptly the umm Radhuma Formation where the Traina evaporite sequence is absent.
   b) The downthrown side sectors are located away from the Simsima Arch axis near the shoreline. The Simsima Limestone in this side is thick sequence and is directly underlain either by Midra Shale or disconformable by Khor Member. As revealed from deep boreholes more than 80 meters thick of massive anhydrite with thin interbedded limestone the Traina Member are recognized in the cross-sections. Therefore, the lateral and vertical variation of the Eocene rock units is controlled mainly by the tectonic activity near the center of the country, along the west and south directions.

Geological Field Observation

During field observations, many karst related features and caves were observed and identified site. Some of them were near the surface and others were observed through excavation cut near the study area (Fig. 3).

The cavities and midjet caves are very frequent and can be seen exposed on steep slopes or near surface of Simsima and Khor carbonate sequence, mainly within the northern and middle sectors (Figs. 3a to 3d). They vary in size from minute openings to ones with dimensions of several decimeters.

Near the contact between the Simsima and Khor members elongated cavities and minute caves are observed along fractures and inferred faults during field trips to the northern sector (Fig. 3a). Furthermore, small caves and large cavities are detected in the top of Simsima carbonate beds as result of dissolution by acidic groundwater (Fig. 3b). On the other hand, in-filled caves are common in the carbonate sequence of the middle sector where the caves were formed as a result of dissolution of the bedrocks followed by deposition of Quaternary fine materials or/and weathering filling the voids of the cave (Fig. 3c) or forming calcite crystals that precipitated on the voids walls (Fig. 3d).

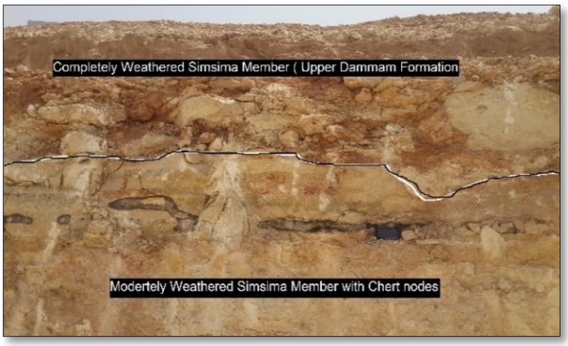

Fig.3b. Karst cavities near surface within the Simsima Layer overlying the Khor Member in the Northern Sector

Fig.3a. Excavation cut near Al Khor showing the highly weathered Simsima Member and chert nodes within Khor Member in the Northern Sector

Fig.3c. Excavation cut near Al Khor, show filling of cavities in Simsima Layer by Quaternary deposits

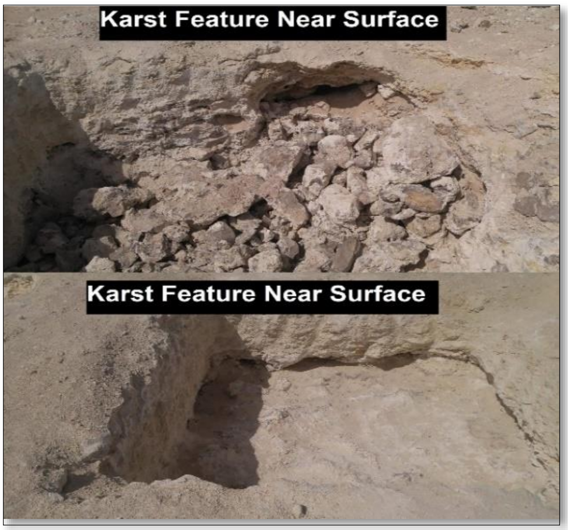

Fig.3d. Excavation near the surface in the Middle Sector shows a karst cavity at the boundary between Simsima and Khor members

Petrographic Investigation

Based on core description, selected samples were investigated for their petrography to identify the rock types based on Folk (1959) and Dunham (1962) classifications, in order to study the relationship between the petrographic rock types and its relation to the karstification processes. Accordingly, ten rock types were recognized (Figs. 4 & 5), their distribution is given in Table (2) and briefly discussed as follow:

- Foraminiferal Wackestone/Packstone (Type 1): This rock type is biomicrite with Wackestone and partly Packstone texture. It is composed of foraminiferal (mainly benthonic) tests embedded in a partially dolomitized micritic matrix (Fig. 4a).
- Nummulitic Packstone (Type 2): This rock type is biomicrite showing Packstone texture in which several entire nummulites tests together with other shell and algal fragments occur in contact with micritic or neomorphic matrix (Fig. 4b).
- Fractured Lime mudstone/wackestone (Type 3): This rock type is fractured bio-dismicrite showing lime mudstone/wackestone texture. It is composed of fossil allochems and patches of sparry calcite aggregates that are surrounded by microcrystalline calcite in contact with ferruginous partially micrite-dolomitic matrix (Fig. 4c).

- Dolomitized wackestone/dolostone (Type 4): This rock type is dolomitized micrite ranging from dolomitized wackestone to dolostone. The crystals in the dolostone are usually compacted and have curved cleavage and undulose extinction containing spots of micrite calcite relics (Fig. 4d & e).
- Calcareous Shale (Type 5): The calcareous brecciated shale of the Midra Member is a very fine ferruginous clastic rock type showing fissility and lamination due to compaction preferred orientation of clay material constituents that parallel to stratification. Petrographically, the rock is highly calcareous laminated claystone and clay-shale with fissility, cracks and fractures and brecciation. The lamination structure is frequent in all the study shales showing desiccation cracks and brecciation appearance. Occasionally; the fractures and cracks contain fine quartz and chert grains (Fig. 4f).
- Dolomitic Lime mudstone/wackestone (Type 6): This rock type is dolomitic biomicrite ranging in texture between mudstone and wackestone varieties. However, the mudstone variety is more dolomitized. it is worth to mentioning that some dolomite crystals were replaced by calcite (high Mg-Calcite as revealed from XRD analysis) through de-dolomitization process under meteoric water environmental conditions (Fig. 5a).
- Dolomitic Lime-mudstone (Type 7): This rock type is dolomitic laminated micrite showing lime-mudstone texture with fossil cavities. The rock is poorly fossiliferous thin laminated cracked lime-mudstone composed of highly dolomitized micrite and neomorphic microspars. All degrees of dolomitization are detected in the

Rock Unit	Sector Name	BH No.	Depth (m)	Petrographic rock type	Core lithology	Rock strength (according to UCS Values)
Dammam Fm (Simsima Member)	Southern	G01	14.70	1.Foraminiferal Wackestone/Packstone	Microcrystalline limestone	Strong
	Northern	P13-05	0.50			
	Southern	G33	15.00	2.Nummulitic Packstone	Chalky limestone	Moderately Strong
	Southern	04	1.30			
		04	9.80			
		04	12.80			
		04	17.50			
	Northern	19 U07	1.15	3.Fractured Lime Mudstone/Wackestone	Marl limestone	Weak
	Middle	DP05	4.70			
	Southern	07	18.50			
	Southern	G01	2.60	4.Dolomitized wackestone	Microcrystalline limestone	Strong
		G01	7.00			
		G05	0,30			
		G05	7.80			
		G33	1.00			
		G33	6.50			
Dammam Fm (Midra Member)	Middle	DP05	7.50	5.Dolomitized Wackestone/Packstone	Calcareous shale	Weak
	Southern	G05	13.00			
		04	20.00			
	Southern	G05	13.2	6.Dolomitized Lime Mudstone/wackestone	Marl Limestone	Weak
		G05	13.80			
Rus Formation (Khor Member)	Northern	19 U07	3.7	7.Dolomitic Lime Mudstone	Chalky limestone	Weak
		19 U07	5.65			
		19 U07	6.3			
	Middle	P12B-04	7.9			
		P12B-04	5.5			
		P12B-04	9.8			
		DP05	11.2			
		DP05	12.3			
	Northern	P13-05	9.3	8. Foraminiferal Packstone	Marl limestone	Weak
	Southern	G05	15			
	Middle	DP05	14.3	9. banded silty cracked Lime mudstone	Marl limestone	Weak
		P12B-04	8.8			

		P13-05	5.3	10. Dolomitic gypsiferous Lime-Mudstone	Marl limestone	Very Weak
		DP05	18.5			

rock type where dolomite rhombs are distributed from dolomitized lime-mudstone up to dolostone (Fig. 5b & c).

- Foraminiferal Packstone (Type 8): This rock type is considered as most predominating biomicrite in the Khor Member (Rus Formation) in the study area. Texturally, it is packstone mainly composed of foraminiferal allochems of different sizes and structures embedded in microcrystalline (micrite) calcite matrix (Fig. 5 d).
- Banded silty cracked lime mudstone (Type 9): This rock type is banded silty micrite showing lime mudstone texture with quartz grains and few scattered microfossils tests. It contains bands of poorly sorted sub-angular to subrounded quartz grains in fine silt size embedded in laminated biomicrite bands (Fig 5e).
- Dolomitic gypsiferous lime-mudstone (Type 10): This type of rock is gypsiferous-dolomitic micrite showing lime-mudstone with few fossil allochems. The rock is composed of a few foraminiferal tests embedded in a dolomitic micritic matrix which is in part gypsiferous. Occasionally, the surrounding dolomitized micritic matrix as desiccated and brecciated may be due to the gypsum crystal`s growth (Fig. 5f).

Table 2. The relationship between the petrographic rock types and rock strength

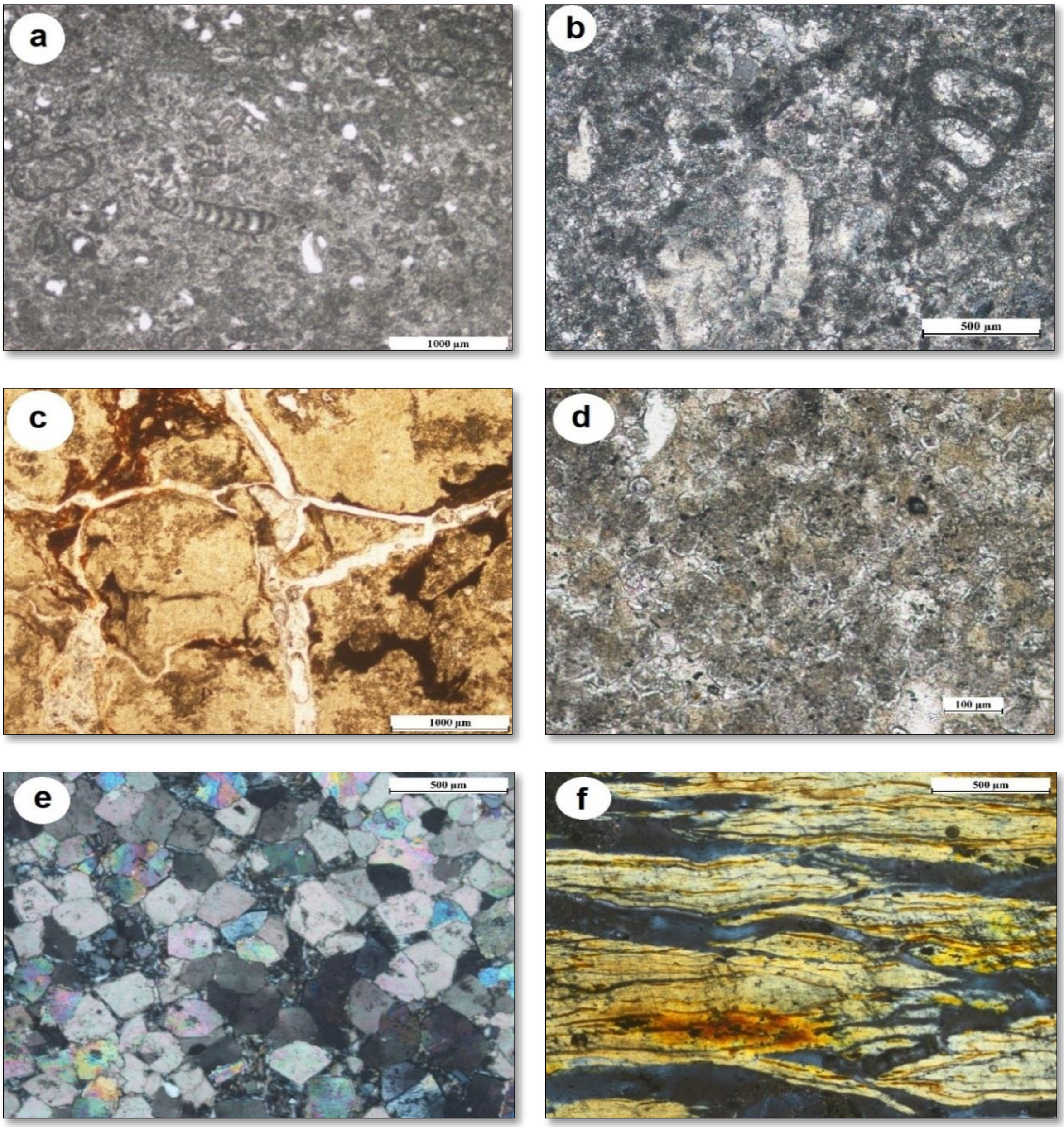

Fig.4.

a: Foraminiferal Wackestone/Packstone: Simsima Member, Northern Sector, BH13-05, depth 0.5m.
b: Nummulitic Packstone: Simsima Member, Southern Sector, BH-G-33, depth 15m.
c: Fractured Lime Mudstone/Wackestone: Simsima Member, Southern Sector, BH-07, depth 18.50m
d: Dolomitized Wackestone: Simsima Member, Southern Sector, BH-G-05, depth 7.0m.
e: Dolostone: Simsima Member, Southern Sector, BH-G-05, depth 7.8m.
f: Calcareous Shale: Midra Member, Southern Sector, BH-G-05, depth 13.0m.

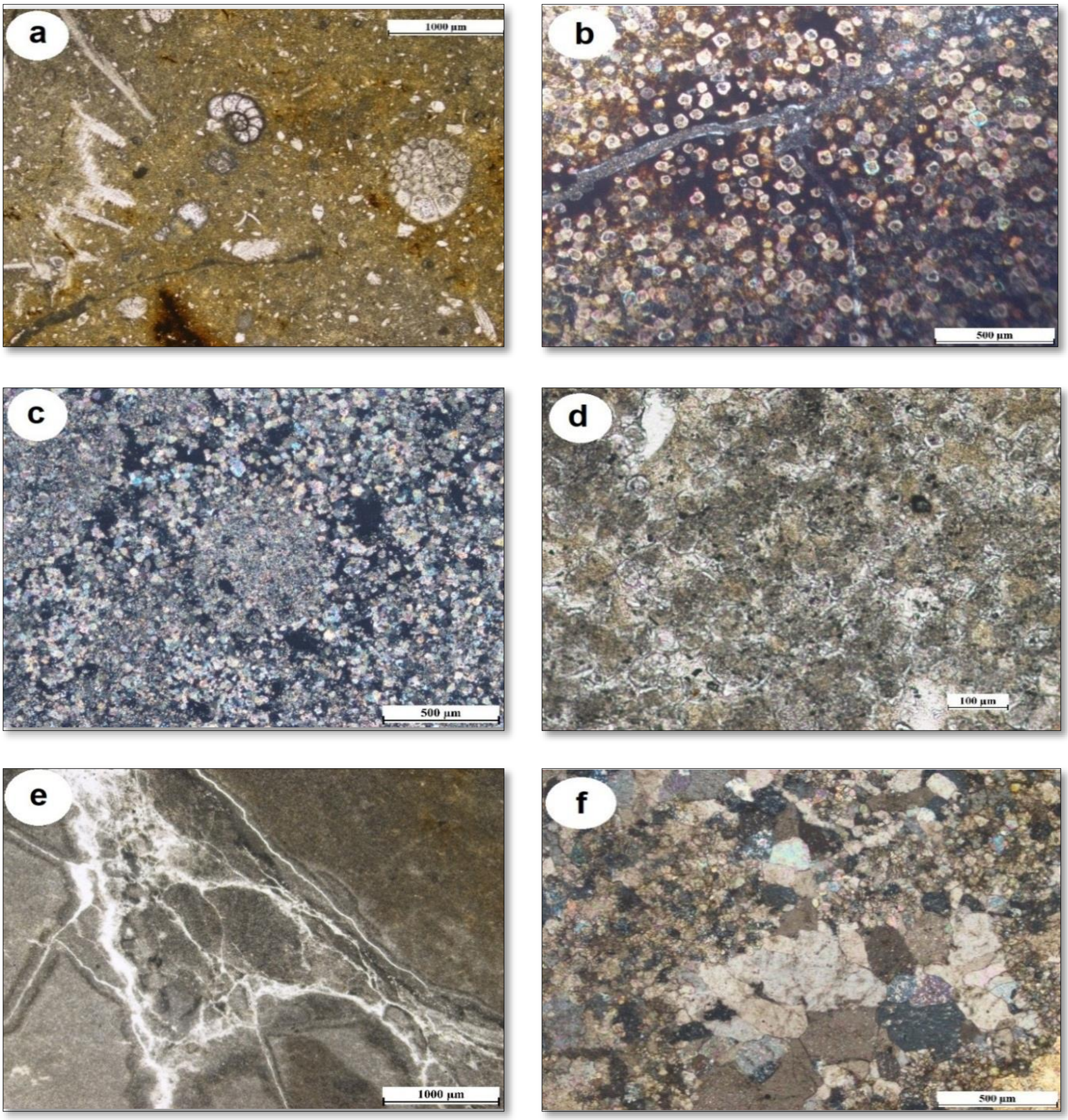

Fig.5.
a: Dolomitized Lime Mudstone/Wackestone: Midra Member, Southern Sector, BH-G-05, depth 15.0m.
b: Dolomitic Lime Mudstone/Dolostone: Khor Member, Northern Sector, BH-19-U-7, depth 3.7m.
c: Dolomitic Lime Mudstone: Khor Member, Middle Sector, BH-12B-04, depth 5.5m.
d: Foraminiferal Packstone: Khor Member, Northern Sector, BH-13-05, depth 9.3m.
e: Banded Silty Cracked Lime-mudstone: Khor Member, Northern Sector, BH-DP-05, depth 14.3m.
f: Dolomitic gypsiferous Lime-Mudstone: Khor Member, Middle Sector, BH-12B-04, depth 8.8m.

The X-ray diffraction (XRD) analysis of both bulk samples of the rock types and clay fractions of some samples from Simsima, Midra and Khor members revealed that Mg-calcite may reach 94% in some dolostones and the dominant clay minerals in all the analyzed samples are mainly palygorskite with traces of smectite. The formation of calcite after dolomite via Mg-calcite through the dedolomitization process at contact between the Simsima and Midra members may be associated with high karstic dissolution potentiality. The dominance of palygorskite which is usually associated with all types of the studied carbonate is believed to be diagenetic (authigenic) in origin in alkaline-hypersaline condition.

Subsurface Karst Detection using MASW Profiles Seismic Wave Velocity Model

The Multi-channel analysis of Seismic Waves is represented in the Seismic profiles (2D Section) where the horizontal distance is represented on the X-axis and depth is represented on the Y-axis and the different colors show the different velocities along with subsurface layers. Wave velocity model will reflect the condition of bedrock properties (e.g. solidity, stiffness and karst potentiality). However, this model is not applicable through the interpretation of carbonate karst features in many cases. This difficulty in the interpretation may be attributed to the wide range of carbonate petrographic types and karst cavity dimensions and depths in addition to fractures-joints architecture. For all these lithological complications the geophysical data were occasionally supported by borehole geotechnical data to improve the geological interpretation certainty of the model application. The shear wave velocity shows a wide range of colors which all represent a different geological significant. The low shear wave velocity represents the weak unconsolidated material and the higher shear wave velocity represents the solid consolidated strong layers. The major categories of velocity model could be further subdivided into five classes exhibiting intermediate properties of rock (or soil) solidification and stiffness. These are from very soft and loose material to very hard and stiff material as follow:

Class 1: extremely low velocity (less than 400m/sec) giving a dark blue area.
Class 2: low velocity (from 450m/sec to 650m/sec) giving pale blue area.
Class 3: moderately high velocity (from 650m/sec to 900m/sec) giving dark green to yellow area.
Class 4: high velocity (from 900m/sec to 1100m/sec) giving yellow to orange area.
Class 5: extremely high velocity (more than 1100m/sec) giving a dark red area.

Poor correlation is observed in some cases where the boring log did not show conditions that could be correlatable with the velocity model. These exception cases are represented by:

1. Upper/shallow low-velocity layers confirmed by geotechnical boreholes are conversely related to hard dolomitic limestone. This case may be due to the presence of pore spaces and micro fracturing within dolomite.
2. Deep high-velocity layers are related to the relatively soft calcareous mudstone and shale of the Midra member as revealed from the megascopic core description. This high velocity may be due to presence of hard intercalated thin layers of chert with the host rock.

Depending on the Geophysical Model created, several subsurface karst cavities and anomalies were recorded along the number of the studied profiles distributed in the five studied sectors in the study area (Table 3). The table shows the distribution of Karst in Simsima Member mainly within the upper layers along the coastal area as result of seawater. Dissolution of Simsima Layers is going through the fracture system within the layer causing the development of subsurface cavities and subsurface infilled cavities filled with fine sediments. Rus Formation shows less karstification effect along the coastal area as an effect of seawater is mainly for the upper layers in addition to the presence of impermeable Midra Shale. Rus Formation near the surface in the western part of the study area shows a high effect of karstification as a result of surface water (rain water) which dissipated through the fractures to the rock-forming dissolution and development of subsurface cavities.

Application of the Seismic Model to detect subsurface Karst cavities

Selected subsurface geophysical profiles were studied for application of seismic model and subsurface karst detections. A correlation between the geotechnical boreholes and the geophysical profiles and distribution of karst within the identified layers were presented in Figure 6. Highly weathered Simsima Member was encountered in the first 5 to 8m along the Northern sector and was represented by the pale blue and dark blue color of low shear wave velocities (Fig. 6a). Simsima Member was directly by Rus Formation and absence of Midra Shale within the area. Rus Formation was represented by medium shear wave velocities of yellow and green, with some relatively weak interbedded layers of chalky limestone. A weak thick layers of Simsima Limestone was presented in the geophysical profiles with very low shear wave velocities and correlated by the geotechnical boreholes in the Eastern sector (Fig. 6b). Simsima Member showing presence of oval to sub-circular karstified zones at the lower part near the boundary between Simsima and Midra. The upper part of Simsima was affected by seawater percolation along the fractures resulting in the karstification process in this layer (Fig 6c). The Simsima Member shows a moderately to slightly weathered layer distributed along the South Eastern sector. This layer was underlying by a weak layer of Simsima as a result of the dissolution of gypsum and calcareous silty material inclusions within the layer (Fig. 6d). percolation of surface and seawater along the fracture system and voids within the upper layers of Simsima in addition to presence of impermeable Midra Member causing accumulation of water along the lower Simsima resulting the weak layer of pale blue and dark blue colors which representing a low shear wave velocity zone.

Different karstification processes distributed along the study profiles and the effect of tectonic and structure activities in the development of karstification within the study profiles control the distribution of karstified layers along the subsurface geological layers (Figure 7). Rus Formation was encountered near the surface in the Northern sector. It was found to be highly karstified filled with karst cavities and distributed randomly along the south part of Northern sector. Near Surface highly Rus Formation was represented by very low shear wave velocity with dark blue colour (Fig. 7a). This is mainly a result of the presence of a shallow impermeable mudstone layer which accumulates the rain-fall surface water near the surface layers causing dissolution processes to lead to the formation of the karst cavities. The surface water percolation along the fracture to deeper layers may be also an encountered case in some locations along the Northern and Middle Sectors (Fig. 7b). In the Southern Sector, Upper Simsima shows a lateral variation in the layer distribution. The upper part is in locations along the study profiles were represented by yellow to green colour with medium shear wave velocity values (Fig. 7c). This was shown occasionally by low shear wave velocity values near the surface and represented by dark blue oval zones. These karst zones were developed mainly by surface water effect on the upper Simsima Layers. The lower Simsima Layer was showing a homogeny in the lateral distribution of the layer along the area. The Layer was showing a high shear wave velocities and was represented by red color. The correlation studies between profiles and studied boreholes show that the lower layer is Chalky to Marly compacted dolomitic Limestone. In the deep layers of Rus, water may be percolated along fractures from the deeper aquifers and settled on the impermeable mudstone layers of Tarina Member causing the formation of Karst cavities in lower layers. These karst cavities are represented mainly by dark blue oval to sub-circular shapes of low shear wave velocities (Fig. 7d). The upper layer of the Rus Formation was showing a low shear wave velocity. A very weak dark blue zone was distributed along the layer (Fig. 7c & d) as a result of water percolation from the deeper aquifers.

Table 3. Detected subsurface karst cavities and anomalies within the study area at different depths. Note their areas and dimensions

Sector	Site Location	Profile Name	Simsima Member			Rus Formation (Khor Member)		
			Depth of Karst Cavities (m)	Total Karst Cavities Dimensions (length x width) (m^2)	Fracture Intensity	Depth of Karst Cavities (m)	Total Karst Cavities Dimensions (length x width) (m^2)	Fracture Intensity
Northern	Junction 19	J19-Line 1	0-5	200	Low	20-25	300	Low
		J19-Line 5	0-5	400	Low	20-25	60	Low
		J19-Line 8	-	-	Low	20-25	125	Low
	Junction 13	J13-L4-2	0-5	40	=	-	-	-
		J13-L5-2	0-3	95	Low	3-10	25	Low
		J13-L7-1	0-5	180	Low	5-17	175	Low
		J13-L8-1	0-6	100	=	10-15	60	Low
Middle	Junction 12B	J12B-L1-1	0-5	100	Low	12-17	50	Low
		J12B-L1-2	0-5	60	Low	5-17	50	Low
	DNST P	DN-Line 1	0-7	280	High	17-22	120	High
		DN-Line 3	0-7	250	Med.	15-20	125	High
		DN-Line 6	0-5	70	High	15-25	170	High
Eastern	Lusail	BR006b	10-22	150	Med.	-	-	-
		H0002	15-22	120	High	-	-	-
		H0003	8-22	180	High	-	-	-
Southern	Abu Nakhla	Line01	0-5	200	Low	22-27	40	Med.
		Line09	0-6,15-20	1100	High	-	-	-
		Line14	0-25	850	High	-	-	-
		Line18	0-6,15-20	1100	High	-	-	-
		Line33	0-6,15-26	650	High	-	-	-
		Line38	0-5,20-25	600	Med.	-	-	-
		6-1	0-10,20-26	1300	Low	-	-	-
		7-4	0-10,15-27	1000	Med.	-	-	-
		8-4	0-7,17-23	450	=	-	-	-
		11-4	0-6	120	Med.	22-28	250	Med.
South Eastern	Al Wakrah	P5 line 5 Part1	0-5,15-20	375	=	-	-	-
		P5 line 5 Part2	0-5,12-22	600	High	-	-	-
		P5 line 5 Part3	0-5,15-20	180	Med.	-	-	-
		P5 line 6 Part2	0-7	700	Low	-	-	-
		J2-BR1-C3	0-6,20-25	1900	High	-	-	-
		J5-BR1-C	15-25	180	Low	-	-	
		M3-BR1-D1	0-7	400	High	-	-	-

(-) = refer to absence of rock unit or not recorded	Med. = Medium	(=) = No Fractures

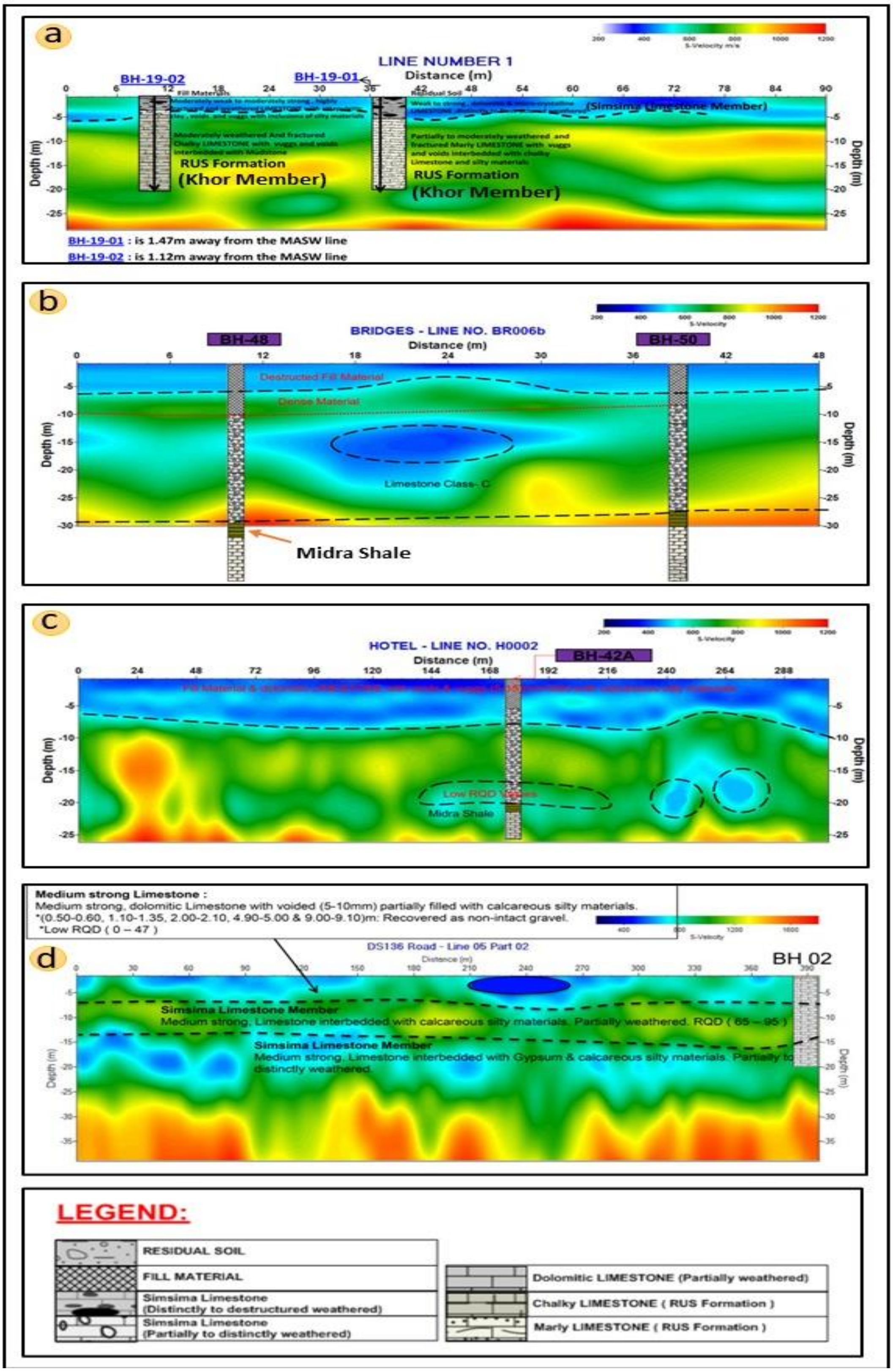
a
LINE NUMBER 1
Distance (m)
BH-19-02
BH-19-01
RUS Formation
(Khor Member)
RUS Formation
(Khor Member)
Depth (m)
BH-19-01 : is 1.47m away from the MASW line
BH-19-02 : is 1.12m away from the MASW line
b
BRIDGES - LINE NO. BR006b
Distance (m)
BH-48
BH-50
Destructed Fill Material
Dense Material
Limestone Class- C
Midra Shale
Depth (m)
c
HOTEL - LINE NO. H0002
Distance (m)
BH-42A
Low RQD Values
Midra Shale
Depth (m)
Medium strong Limestone :
Medium strong, dolomitic Limestone with voided (5-10mm) partially filled with calcareous silty materials.
*(0.50-0.60, 1.10-1.35, 2.00-2.10, 4.90-5.00 & 9.00-9.10)m: Recovered as non-intact gravel.
*Low RQD (0 – 47)
d
DS136 Road - Line 05 Part 02
BH 02
Simsima Limestone Member
Medium strong, Limestone interbedded with calcareous silty materials. Partially weathered. RQD (65 – 95)
Simsima Limestone Member
Medium strong, Limestone interbedded with Gypsum & calcareous silty materials. Partially to distinctly weathered.
LEGEND:
RESIDUAL SOIL
FILL MATERIAL
Simsima Limestone (Distinctly to destructured weathered)
Simsima Limestone (Partially to distinctly weathered)
Dolomitic LIMESTONE (Partially weathered)
Chalky LIMESTONE (RUS Formation)
Marly LIMESTONE (RUS Formation)

Fig.6. Subsurface profiles and correlation with the geotechnical boreholes to detect the subsurface layers and karst cavities within the layers

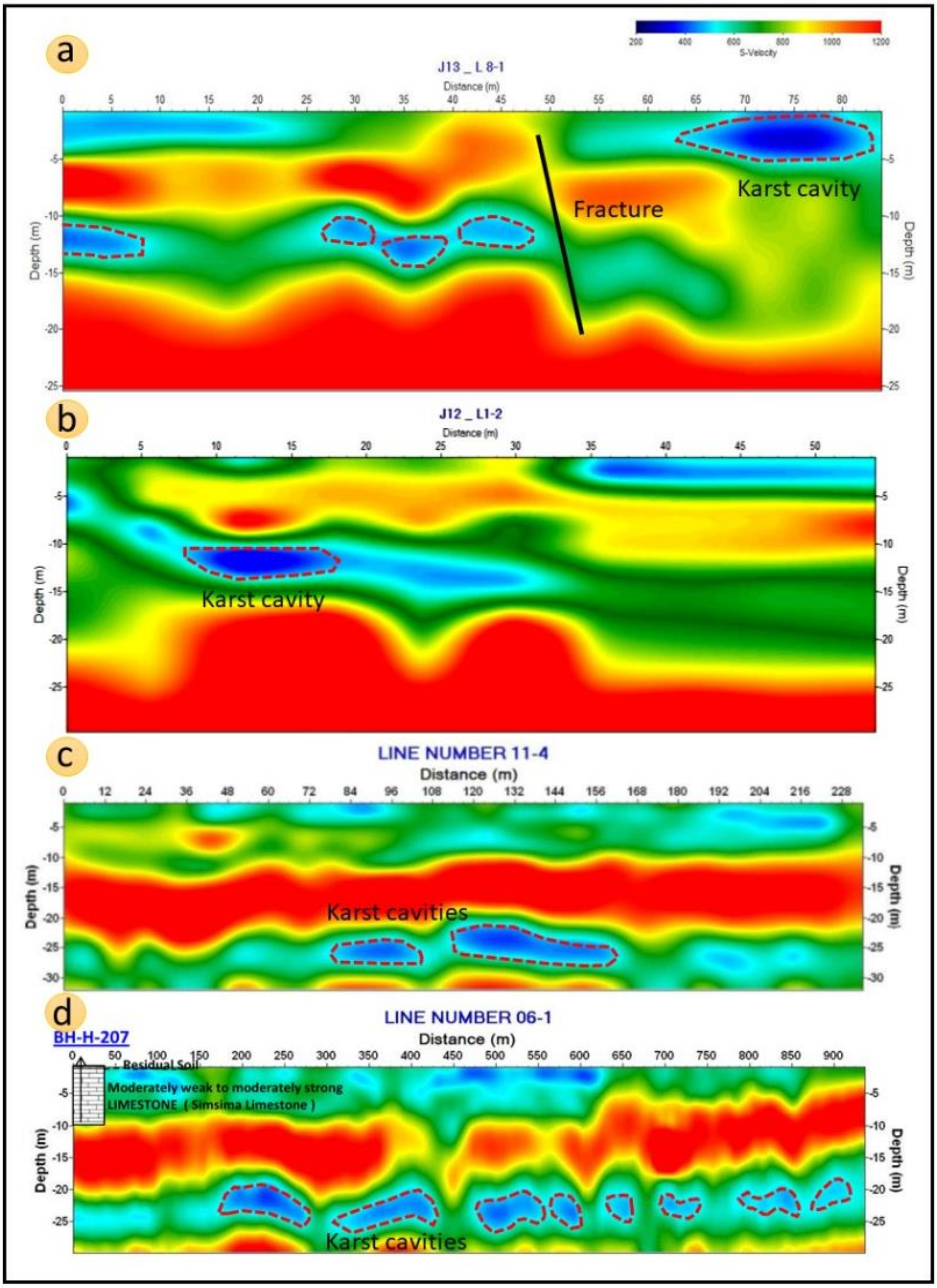

Fig.7. Selected study profiles show karstification within weak subsurface layers inside the study sectors and distribution of karst cavities within the area

Impact of Karstification effects on the geotechnical properties

Two main geotechnical parameters were investigated, these are: rock quality designation (RQD%) and unconfined compressive strength (UCS). To reveal the impacts of karstification effects on the geotechnical properties the values of the RQD and UCS classes were correlated together and with the collected data derived from rock units, petrographic rock types distributions as well as from the interpreted results of the MASW profiles along the different sectors (Table 4).

It is indicated that the expected positive correlation between UCS and RQD values seems to be unstable in most cases (Table 4). This not linear relationship may be due to the differences in technical conditions under which the UCS and RQD values are obtained. In this respect the UCS values are obtained from laboratory testing on the cylindrical specimen while those of the RQD represent the percentage of the intact core pieces larger than 10cm in the drill core`s total length. This unstable relation may be further due to the variation of the occurrence and magnitude of the karstification along with the stratigraphic layers as detected In Table 3.

Through Table 4, it was noticed that Simsima Limestone layers are presenting the highest values of UCS while the highest RQD% values are recorded with the Rus (Khor) Limestone. The Low values of the RQD% in a moderately strong layer (e.g. in Simsima, BH-57 at depth 12m. and in BH-G-05 at depth 0.3m) may be also attributed to mechanical fracturing during the drilling processes. In Conclusion, the highly karstified carbonate layers in any rock units generally reduce both values of UCS and RQD% but they are not correlate-able together which might be causing misleading during the geotechnical evaluation for construction application.

The comparison of rock strength classes with the identified petrographic rock types (Table 2) revealed that the UCS values in the carbonate rocks of the Simsima Member are high relative to those of Midra and Khor members. However, the direct relationship between the rock types and the rock strength is not clear (Table 2) due to possible impacts of other factors including karstification effects.

On the other side, Simsima Limestone Layers show low shear wave velocity values due to the presence of karst, secondary material and cavities within these layers. Rus Formation shows an average UCS values relatively between very weak to weak. The Rus Formation (Khor Member) shows a medium shear wave velocity as it is highly compacted and contains lime mud and mudstone layers unless appearance of karstification which leads to reduced shear wave velocity (Table 4).

Some very weak layers that show RQD values ranging between 45-77%, in Rus Formation (e.g. BH-U-07 & BH 57) shows a very high shear wave velocity values, this is due to the chemical composition of chalky limestone which is mainly of compacted lime mudstone and to intercalated with mudstone layers in between the limestone layers. This may lead to a false interpretation of seismic profiles which need to be correlated with the geotechnical and geological data to improve interpretation certainty.

In Conclusion, as the effects of karstification increase in its severity, magnitude and spatial distribution, the original texture and composition and consequent geotechnical properties of the bedrocks will be modified. Under these conditions, we would expect to see poor or no correlation between the geotechnical parameters values and the interpreted results derived from petrographic rock types, seismic wave velocity indifferent rock units as given in Table 4.

Table 4. Integrated data from geological, geotechnical and geophysical analyses

BH NO.	Sector Name	Depth of Sample	Rock Unit	Geotechnical characteristics				Seismic Wave (Vs m/s)
				UCS (MPa)	Rock Strength	RQD %	Rock Quality	
BH - U 07	Northern Sector	2.5	Simsima	18.77	Weak	40	Poor	400
		5.5	Rus	16.14	Weak	77	Good	550
		8.5		18.5	Weak	72	Good	700
		19.5		3.5	V. Weak	45	Poor	850
BH P13 -05		0.5	Simsima	-	-	48	Poor	650
		1.3		-	-	68	Fair	400
		9.3	Rus	-	-	55	Fair	700
BH R 3		3.5		36.0	M. Strong	50	Poor	450
		18.5		8.4	Weak	20	V. Poor	700
BH-P 12B-04	Middle Sector	5.5	Rus	-	-	45	Poor	600
		9.8		-	-	49	Poor	600
BH-12B-16		4.5	Rus	19.31	Weak	30	Poor	550
		9.5		6.45	Weak	60	Fair	850
		18.5		2.5	V. Weak	85	Good	600
DP-05		4.7	Rus	-	-	17	V. Poor	550
		7.5		-	-	0	V. Poor	450
		18.5		-	-	0	V. Poor	750
BH-42A	Eastern Sector	7.3	Simsima	16.06	Weak	10	V. Poor	500
		20.1	Midra	7.13	Weak	77	Good	600
		21.5	Rus	5.93	Weak	35	Poor	600
BH-57		12	Simsima	38.86	M. Strong	41	Poor	550
		22.3		15.69	Weak	47	Poor	700
		37	Rus	7.01	Weak	52	Fair	1200
BH G 01	Southern Sector	2.6	Simsima	32.8	M. Strong	86	Good	1200
		14.7		35	M. Strong	50	Poor	700
BH G 05		0.3	Simsima	40	M. Strong	24	V. Poor	600
		7.8		36	M. Strong	58	Good	600
		15	Midra	16	Weak	35	Poor	600
BH G 33		1	Simsima	21.5	Weak	42	Poor	500
		15		16	Weak	26	Poor	600
02-BH03	South eastern Sector	2.3	Simsima	18.99	Weak	85	Good	1200
		20.0		13.02	Weak	60	Fair	950
88-BH05		1.0	Simsima	9	Weak	80	Good	700
		13.8		32.79	M. Strong	75	Good	850

BH NO.	Sector Name	Depth of Sample	Rock Unit	Geotechnical characteristics				Seismic Wave (Vs m/s)
				UCS (MPa)	Rock Strength	RQD %	Rock Quality	
BH-EN115		8	Simsima	11.79	Weak	50	Poor	1500
		17.6		40.71	M. Strong	90	Good	1200
BH-EN190		6	Simsima	8.4	Weak	75	Good	600
		20.7		20.91	Weak	75	Good	900

Integrated Factors Controlling the karst hazardous potentiality and geotechnical evaluation

The geotechnical evaluation in the study area depends on the quality and strength properties of the Eocene bedrocks which are highly affected by the spatial distribution of the subsurface karst hazards. Therefore, the integrated causative factors (e.g. lithological, structural and hydrological factors) that control the karstification hazard potentiality are the same factors controlling the geotechnical properties and general evaluation for engineering application. The following is a brief discussion of these factors.

1. The presence of thick homogenous Simsima limestone and Rus carbonate sequences with low terrigenous contents have good characteristics for karst development. They have weak planarity which may give better opportunities for more open spaces and further karstification.
2. It is indicated that the Majority of karst cavities and karstified openings are more extensively developed within the nummulitic coarse-grained limestone of the Simsima member particularly in the Eastern sector. Furthermore, fine-grained micritic limestones of the study members show extensive karst cavities along planner fractures, particularly when they are intercalated with calcareous mud rocks and marl.
3. The presence of subsurface impermeable Midra shale in the eastern (Lusail) and south eastern (Al Wakrah) sectors may cause in ground water rising and consequently it may assist in the development of karst forms within the overlapping shallow Simsima limestone and cause in the preservation of the older gypsum layers.
4. It is found that genetic interrelation between gypsum in the Rus Formation and both calcite and dolomite in the Dammam Formation has a profound effect on karstification. For instance, karstification can take place where dolomite is in subsurface contact with gypsum dissolution drives the precipitation of calcite, thus consuming carbonate ions released by dolomite. Generally, during karstification processes calcite is more soluble than dolomite in the study of carbonate rock.
5. It is indicated by many authors (e.g. Eccleston etal., 1981. Sediq and Nasir, 2002 and Duggan, 2014) that the primary karst forming process is essentially selective dissolution of the Rus gypsum layers by paleo groundwater circulation. Accordingly, karst feature geometry is correlated directly with the presence or absence of subsurface gypsum layers. In the central Qatar province which represented by the northern and middle studied sectors, the subsurface gypsum seems to be dissolved and the overlying beds are collapsed to form karst depressions and most sinkholes. This Gypsum dissolution is commonly widespread in the areas where Midra shale is absent.

The karst development depends mainly and initially on the number of open spaces through fractures, joints and bedding planes within The Eocene carbonate bedrocks. The karst features along the NE-SW structure trend particularly when it intersected with other trends (e.g. NNW-SSE trend) are well observed in the study sectors. The formation of these features may due to dissolution of the bedrocks through groundwater ascending or/and seawater percolation along major fractures from a deeper aquifer to shallow levels particularly in Lusail and Al Wakrah Sectors.

Karst Hazard Potential Map

In the study area many subsurface construction operations (e.g. excavation for building and tunneling) are carried out in carbonate rocks which occasionally are karstified. However, the lack of subsurface geotechnical studies has created unexpected engineering conditions. Therefore, the present study aims to provide a reliable geotechnical data in the form of a guide map showing the spatial distribution of the karst hazard potentiality within the study coastal area. This Map was constructed based on the integration of the borehole correlation charts models (Fig. 2), and geophysical and geotechnical core data (Tables 3 & 4). Accordingly, the map was divided into four main risk zones: (1) very high, (2) high, (3) medium and (4) low to medium risk zones (Fig. 8). The general characterization of these could be summarized as follows:

(1) Very high-risk zone:

This zone occupies the onshore eastern and south eastern sectors of the Lusail and Al Wakrah districts (Fig. 8). It is almost flat with ground elevation ranging between 2 to 6m above sea level. The subsurface bedrocks in this zone consist of Simsima, Midra and Khor members. The Simsima Member is composed of thick layers (15-25m thick) of highly karstified and fractured dolomitic Limestone showing several voids and cavities near the contact with the underlying Midra Member which is mainly represented by 3-5m of calcareous shale and marl layers. The karst cavities are intensively concentrated at depths of 7-17m at Lusail district while the area is very common at depth of 3-12m in Al Wakrah district as given in Table 3. The Simsima Limestones which constitutes the shallow and deep foundation bedrocks, range from very weak to weak rocks as given in Table 4. The underlying Khor deeper bedrocks which ended by boreholes at depth of 40m, is very weak chalky and marly Limestone with mudstone intercalation (Table 4). The Karst cavities occur in these deeper bedrocks at 20m depth in Lusail district while several intensive karst cavities are common at depth 22-25m in Al-Wakrah (Table 3).

(2) High-risk zone:

This zone occupies the onshore Khor district to the east of the northern sector showing moderate to low relief near the shoreline (Fig. 8). Topographically, it is almost flat to the slightly undulated ground showing a general eastern slope ranging from 16m above sea level on average to near shoreline. This zone is characterized by the occurrence of highly karstified Simsima Limestone with variable thickness. Both Simsima and the underlying Khor sequence form the foundation bedrocks where Midra Shale seems to be almost absent. This sequence contains very weak to weak rocks similar to those in the onshore zone rather than in the inland northern zone.

(3) Medium risk zone:

This zone occupies the southern sector and extends northward to include the southeastern corner of the middle sector (Fig. 8). The zone shows relatively high relief, particularly its southern part at Abu Nakhla district where it ranges from 23m to about 40m above sea level. Based on the boreholes and Seismic profile data the zone sequence consists of Simsima Limestones (15-19m thick), Midra Shale and Marl (1-4m) and Khor karstified fine-grained carbonates that ended by the boreholes and profiles at more than 40m. The Simsima consists of highly karstified and fractured dolomitic limestone interbedded with layers of reddish attapulgite clays which may show with groundwater some hazardous swelling behavior. In the relatively lower relief the Simsima sequence is thinner and underlain by the thick karstified dolomitic and fossiliferous limestone of the Khor Member as shown in the Seismic profile. Some karst open cavities are frequently scattered especially at shallow depth along the disconformity boundaries within the top of the thick Khor and base of the thin Simsima sequence. However, in normal cases the cavities are located at depths of 3-23m and 20-25m in the Simsima and the Khor members respectively (Table 3). Both sequences show moderate values of UCS (Table 4).

(4) Low to medium risk zone:

This risk zone occupies the majority of the northern and middle sectors (Fig. 8). It is characterized by the occurrence of the near-surface or surface thick Khor Member sequence which is occasionally covered by thin Simsima Layers. The zone is almost flat to the slightly irregular ground with an average elevation of 20m above sea level. The karst cavities in the thin layers of Simsima are located at depths 3-5m while those of weak Khor bedrocks are scattered at 10-22m depth (Table 3). Accordingly, the bedrocks for both shallow and deep foundations are located within the Khor sequence which shows low to moderate risk potentiality.

The following are brief guidelines (Table 5) revealed from the karst hazard potential map (Fig. 8).

The distribution of the rock units: Simsima, Midra and Khor members are variable in thicknesses, erosional and dissolution situations due to their structural setting. Accordingly, the risk zones in the map (Fig. 8) and Table 5 could be clustered into two groups of zones. The first one is located within the upthrown side of the major NE-SW inferred fault (see the geological map) and includes the risk zones LM and H (Table 5). The Simsima Limestone in this group is relatively thin while the thick Khor sequence is considered as the main bearing bedrock.

The second group including the risk zones VH and M occupies the downthrown side of the fault (Fig. 8). It is indicated that the Simsima sequence is relatively thick in these zones and is considered the main foundation bedrock. The karst cavities and openings are extensively developed through fractures, joints and bedding planes within the Simsima rather than in Khor carbonate bedrocks.

The presence of the Midra Layers underneath the Simsima bedrock increases the risk potentiality, particularly near shoreline zones where karstification could be extensively developed by the dissolution of the bedrocks through ascending or/and percolation of groundwater and sea water along the structural weakness plains.

The shallow water table closed to the sea level may allow seawater intrusion through faults, fractures along the coastal bedrocks and consequently the development of subsurface karst cavities.

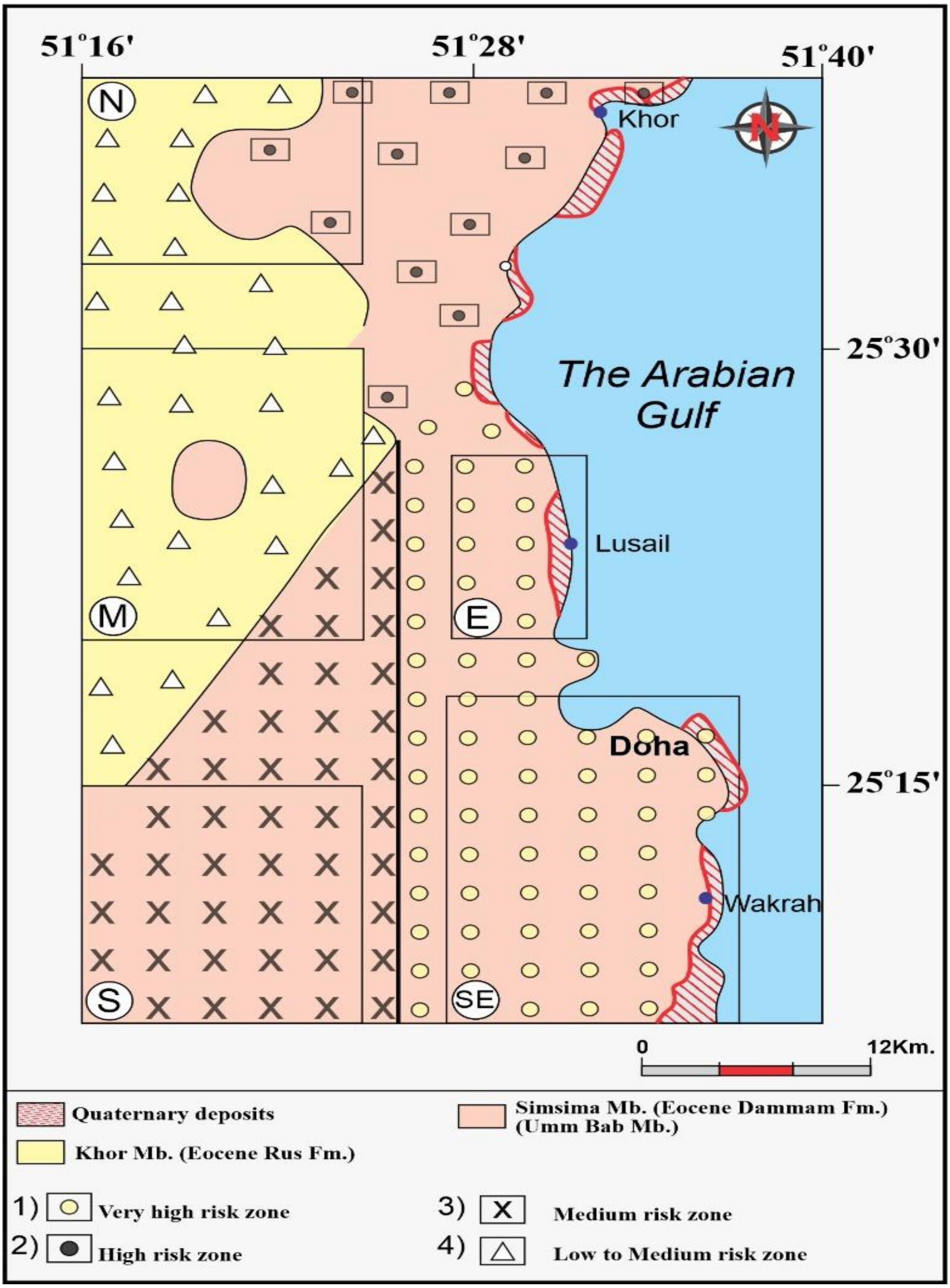

Fig.8. Karst Hazard distribution map along the study area

Table 5. Characterization of the mappable risk zones and their controlling parameters

Controlling Parameter / Risk zone	Relief Pattern [(a)]	Water Table depth [(b)]	Major structural system [(c)]	Rock Unit characterization		
				Simsima [(d)]	Midra [(e)]	Khor [(d)]
1) Very High (VH)	Low relief in Lusail Moderately in Wakrah	Shallow near the sea level	The zone is located in the downthrown side	Thick highly karstified	Thin layer	Thick to thin
2) High (H)	Low relief near shoreline moderate due west	Moderate to shallow near the sea level	The zone is located in the upthrown side	Thin and increase in thickness and karstification toward shoreline	eroded	Thick moderately karstified
3) Medium (M)	High relief due south to high due north	Deep higher than the sea level	The zone is located in the upthrown	Thick highly karstified	Thin layer	Thick to thin
4) Low to medium (LM)	High to moderate relief	Deep higher than the sea level	The zone is located in the upthrown	Thin moderately karstified	eroded	Thick moderately karstified

(a) Low relief is more hazardous than high.

(b) Shallow is more hazardous than deep.

(C) The downthrown side zones are more hazardous than those of the upthrown zones.

(d) The thick Simsima sequence is more hazardous than thin Simsima than thick khor sequence.

(e) The presence of the Midra shale is more hazardous than its absence.

V –CONCLUION

1. The present study emphasizes on evaluation of geoenvironmental hazards in the central-eastern coastal area of the Qatar Peninsula where Karst depressions and subsurface karst cavities are mainly developed in the Eocene carbonate bedrocks. These hazardous karst features are variably distributed in the study sectors causing potentially risky impacts on the current infrastructure facilities and on the future development planning.
2. Based on the field observation and correlation with the regional geomorphological setting several coastal landforms and karst features were detected and described. Using the constructed geological map and the boreholes correlation chart models, three schematic subsurface cross geological sections were constructed to demonstrate the tectono-sedimentation and dissolution controls.
3. The megascopic core description, and microscopic and XRD investigations added a significant contribution to the precise geotechnical evaluation of the karstified bedrocks of the Simsima wackestone-dolostone, Midra and Khor lime mudstone calcareous shale-mudstone. These rock types show variable values of the geotechnical parameters (e.g. UCS and RQD% depending on their petrographic characteristics as well as the diagenetic and karstification impacts on the rock quality.

4. In the present study where the karst cavities and fractures dominate the carbonate bedrocks integration of the geotechnical, geological and geophysical data should be considered to avoid the possible mis-interpretation of MASW Profiles. An applicable depth Seismic wave velocity model was proposed to detect the subsurface geoseismic layers and to identify and delineate karst cavities. This proposed model is based on the correlation of the velocity classes revealed from the MASW profiles with the geological significance of nearby geotechnical verification boreholes. In this respect, the reasons and conditions for the occasionally poor correlation between the seismic wave velocity and geological interpretation were discussed to reveal the possible causative controlling factors. Based upon this proposed model which improves the interpretation certainty, the karst hazard potentiality in the different physiographic sectors was determined.
5. The integration aspects of the geotechnical data with the geological and geophysical data were discussed to reveal the factors controlling the spatial distribution of the karst hazards development. potentiality and consequently control the site selection for land-use planning. The petrographic rock type and hydro-structural condition seem to be the main causative factor controlling the karstification potentiality and consequently controlling the engineering rock quality.
6. The lack of subsurface geotechnical reliable data that are required for construction operation and excavation for tunneling has created unexpected engineering conditions. In this respect, the present study may contribute to providing these required data through the construction of a guide map showing the spatial distribution of the karst hazard potentiality zones. It is indicated that karstified Simsima and Khor layers are considered as foundation bedrock in the onshore and inland zones respectively.
7. Due to the highly karstified hazardous impacts on the Simsima rather than Khor bedrocks additional precautions should be taken into consideration to avoid the predicted geoengineering problems. In the very high-risk zones along with the coastal Khor, Lusail and Al Wakrah districts a pile foundation may be the only solution to avoid these problems. The present model of the integrated geological, geophysical and borehole geotechnical data packages should be provided before any new regional engineering projects.

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