Arab J Geosci (2015) 8:1535–1547
DOI 10.1007/s12517-014-1281-6

ORIGINAL PAPER

Recognition of quartz geodes in the Upper Cretaceous Wadi Umm Ghudran Formation, Ras En Naqab, South Jordan

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Received: 6 May 2013 / Accepted: 16 January 2014 / Published online: 7 February 2014

Abstract Quartz geodes are spectacularly displayed at Ras En Naqab where hundreds of geodes have weathered from their host chalky limestone and sandstone beds and scattered on slope surfaces. Geodes of different sizes, shapes and fillings appear in four horizons of the shallow marine sediments of the Upper Cretaceous Wadi Umm Ghudran Formation in South Jordan. They are characterised by a wide areal extent, but limited stratigraphic distribution, and as such, they represent a distinctive stratigraphic marker horizon. Ghudran geodes are mostly milky white in colour, botryoidally and crystalline in shape and range in diameter from 3 to 30 cm or more. It is believed that the formation of geodes took place in cavities, after complete dissolution of pre-existing fossils, which left no trace of their internal microstructures but only faint appearance of external moulds. Chalcedony and microcrystalline quartz occur as cavity linings and in some samples as cavity filling. The structure of the silica geodes begins with chalcedony in its outer rim followed, internally, by microcrystalline quartz and ends with prismatic quartz crystals in the central part. Spot analysis indicates that the geodes composed totally of Si and O with traces of Al (0.05 %). The silica-rich solutions that formed the geodes were possibly derived from the weathering of the overlying Amman Silicified Limestone Formation and the infiltration of chemical products by the action of groundwater. Investigations showed that the crystallization went slowly under equilibrium conditions and formed from the same silica source.

Keywords Geode · Silica · Umm Ghudran · Quartz · Cretaceous · Jordan

Introduction

Geodes are defined as spherical, hollow concretionary rock bodies containing crystalline structures that vary in chemical composition, size, colour, density, internal shape and origin (Bassler 1908; Chowns and Elkins 1974; Maliva 1987; Maliva and Siever 1988, 1989; Gao and Land 1991; Makhlouf et al. 2003). These geodes are rough, dull-looking spherical objects resembling mud balls, but they are lined with silica crystals of various types. Geodes are divided into two categories depending on whether they occur in sedimentary or igneous rocks.

The first requirement for their formation in sedimentary rocks is the presence of a cavity or hollow space in limestone, marlstone or chalk when a mineral nodule or concretion dissolved, or a buried animal decayed (Bassler 1908; Chowns and Elkins 1974; Maliva 1987; Maliva and Siever 1988, 1989; Gao and Land 1991; Makhlouf et al. 2003). Evaporite cavities were also suitable sites for quartz geodes developments. Quartz occupying anhydrite cavities were described by Henchiri and Slim-S'himi (2006) from Tunisia Eocene marine sediments, when silicification began in the outer parts of the anhydrite cavity of the precursor nodule or concretion.

The geodes described here range in size from a few centimetres to tens of decimetres in diameter. The colour of a geode is determined by impurities in the silica or quartz crystals. Quartz is the most common mineral found in geodes but numerous other types of minerals can fill the cavities such

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as calcite, barite, selenite, marcasite, sphalerite and pyrite, although none of these minerals was found in our study.

Most quartz is milky white, but impurities may tint it other colours; pink, purple, yellow, smoky grey or clear. In most cases, a chalcedony layers lie between the central crystals and the outer geode rim. This chalcedony layer consists of microcrystalline quartz crystals (Bassler 1908; Elorza and Rodriguez-Lazaro 1984; Maliva and Siever 1988, 1989; Gomez-Alday et al. 2002; Makhlouf et al. 2003).

Quartz geodes are an interesting sedimentological feature since they allow reconstruction of the burial history of the host sediment. Moreover, very few occurrences have been studied geochemically and isotopically. Economically, the value of geodes is based on their colour, mineral content and hardness. In other areas of the world, geodes occur in different colours such as red, violet and yellow. The variable colouration of some geodes makes them among the most valuable ornamental and semi-precious stones.

The objective of this study was to investigate the sedimentological, petrographic and morphological characteristics of the quartz geodes and their host rocks. This study also shows that they formed through diagenetic processes. In addition, this study has implications for palaeoenvironmental and diagenetic changes in the Wadi Umm Ghudran Formation sediments based on textural and mineralogical data. The studied quartz geodes were also documented in previous investigations performed in the study area by Pufahl et al. (2003). Similar early diagenetic mobilization of silica in chert, chalk and phosphorite sediments of the Wadi Umm Ghudran Formation have been described from deeper water settings in north central Jordan (Powell and Moh'd 2012).

Geological setting

The quartz geodes are scattered within four distinct horizons of the marine sediments of the Upper Cretaceous Wadi Umm Ghudran Formation (Table 1) at Ras An Naqab in South Jordan (Figs. 1, 2, 3a–d). The Upper Cretaceous Wadi Umm Ghudran Formation is widespread over northeastern and southern Jordan (Powell and Moh'd 2011). The age of the formation is Santonian to Campanian and represents the basal part of the Belqa Group and is overlain by the Amman Silicified Limestone Formation and is underlain by the Wadi As Sir Limestone Formation, the topmost unit of the Ajlun Group (Masri 1963; MacDonald 1965a, b; Parker 1970; Powell 1989).

Facies associations

The Umm Ghudran Formation is 90 m thick in the study area at Ras An Naqab (Figs. 2, 3a,b) and consists of glauconitic sandstones, fine- to medium-grained varicoloured cross-bedded sandstones in the lower part passing upward into clay, colour banded sandstones, siltstones, sandy limestones, dolomitic siltstones, iron crusts and quartz geodes (Fig. 3c). Among the fossils present are bivalves, plant remains, wood fragments, bone fragments and shell fragments, fish (shark) teeth and fossil wood (Moumani 2002). The formation shows broad lateral and vertical changes in lithofacies. It makes moderate to steep slopes (Fig. 3a) due to the predominance of sandstone, clay and calcareous sandstones.

The depositional environment of the chalk facies in north and central Jordan is pelagic deep marine, and the limestones were deposited in a shallow marine environment, with offshore banks forming the sandy facies in the south (Powell 1989; Powell and Moh'd 2011). Large-scale, flat based cross-stratified sand banks indicate a moderate water depth, where sand was reworked by storms and waves into offshore banks (Powell 1989). The depositional environment of this formation probably ranged between fluvial-dominated coastal plain, shallow open marine and marginal marine (Moumani 2002).

Methodology

More than hundred quartz geodes were collected from the Umm Ghudran Formation exposed at Ras En Naqab in South Jordan (Fig. 3d) to investigate the shape, size, mineralogy and texture (Tables 2, 3 and 4). The dimensions and geometry of the geodes are described (Table 2) according to the scheme of Selles-Martinez (1996). The geodes were measured to describe their shape according to Blatt et al. (1972). Some of these geodes were broken open in order to describe their interiors.

Selected quartz grains in the Ghudran geodes were studied by scanning electron microscope (SEM) at Al Hussein Bin Talal University SEM Lab. The utilized SEM is Jeol 6060

Table 1 Stratigraphic setting of the Wadi Umm Ghudran Formation (after Masri (1963); MacDonald (1965a, b); Parker (1970); Powel (1989))

Age			Group	Formation	Lithology
Era	Period	Epoch			
Mesozoic	Late Cretaceous	Santonian	Belqa	Amman silicified limestone	Chert, Limestone, Chalk, Marl, Phosphate
		Coniacian		Wadi Umm Ghudran	Chalk & Chalky marl
		Turonian	Ajlun	Wadi As Sir	Limestone, Dolomite, Marl, Chert nodules

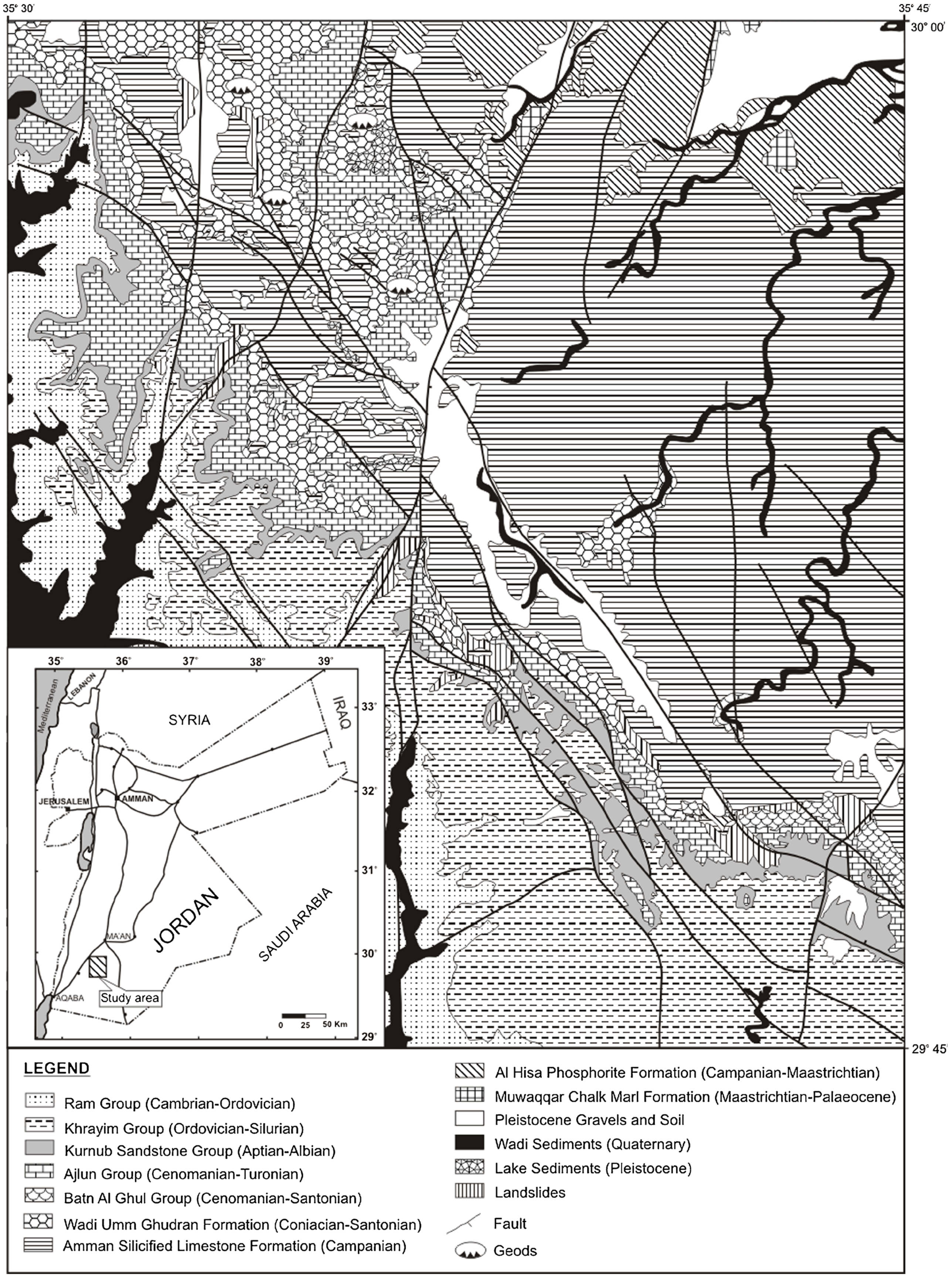


Fig. 1 Location and geological map of the study area at Ras An Naqab, South Jordan

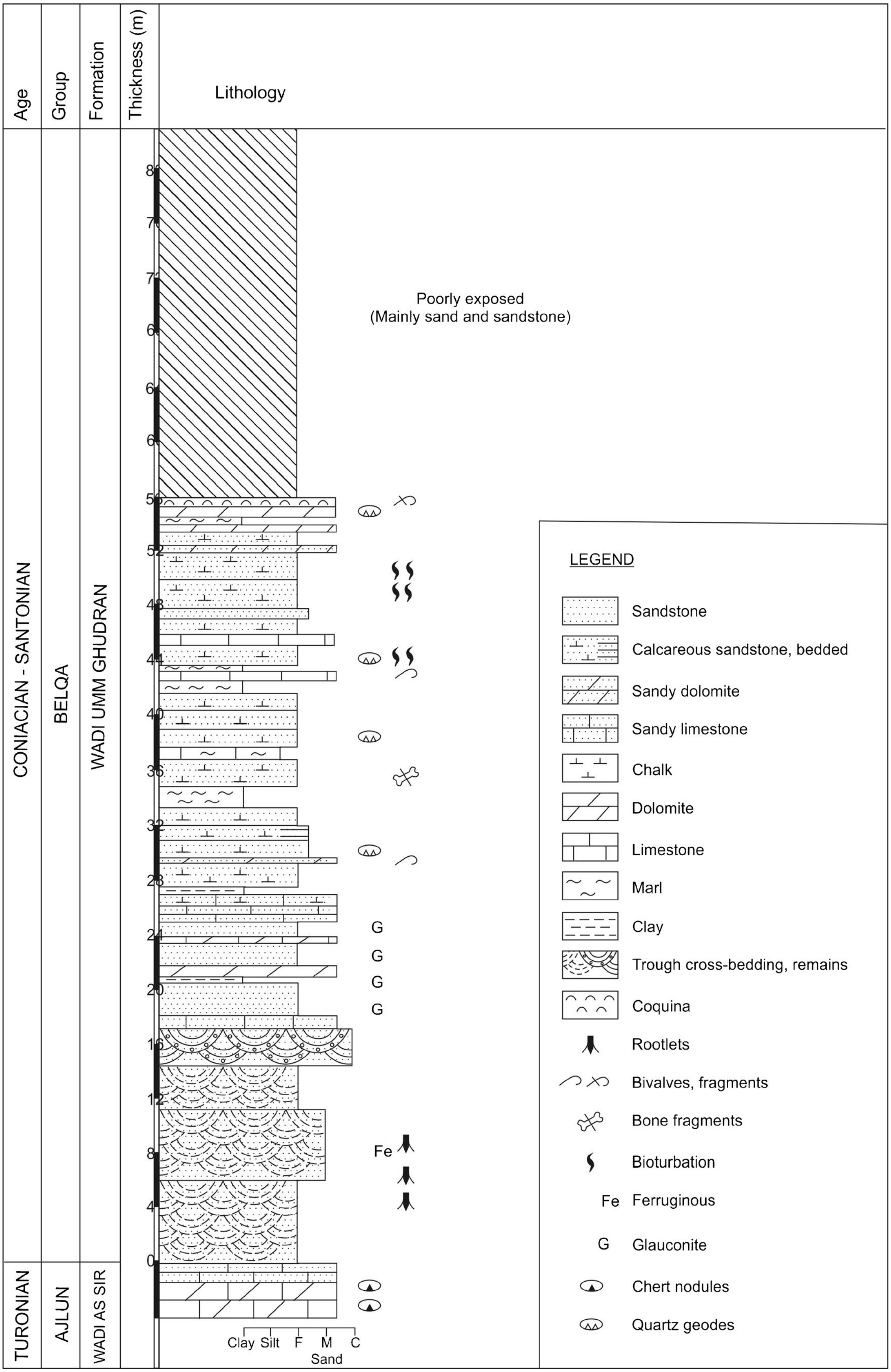


Fig. 2 Graphic logs of the Wadi Umm Ghudran Formation along Ras An Naqab Escarpment, South Jordan

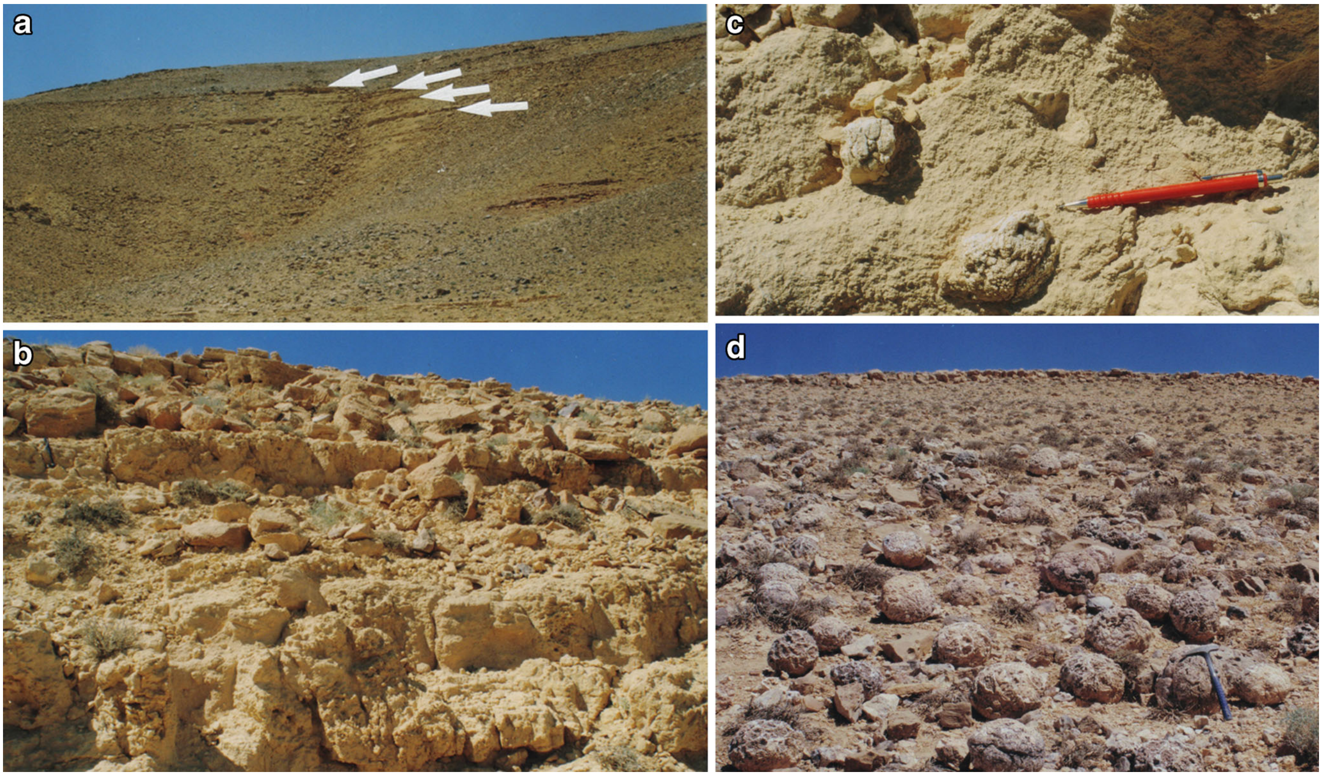


Fig. 3 Field view of: **a** Outcrop of Umm Ghudran Formation, **b** nature of Umm Ghudran strata, **c** prominent in situ quartz geodes (pencil is 15 cm long) and **d** weathered scattered quartz geodes on the slope of the section (hammer is 28 cm long)

instrument-high vacuum, equipped with a link 10000 Energy Dispersive Spectrometry (EDS) system and coupled with back-scattered electron (BSE) and secondary electron image (SEI) microanalyses. Percentage of errors is ±2 %. The SEM-BSE technique allows the determination of the degree of crystallinity in a mineral, enabling the possible interpretation of the silica phase present, while SEM-SEI was used to identify the elementary analysis content of the silica and associated trace elements which incorporated in the geodes.

Geodes description

Exterior features

From the stratigraphic point of view; the presence of quartz geodes in certain beds is considered as a diagnostic feature of specific horizons that can be used as key beds for local to regional correlation purposes (Fig. 3c). Some of the geodes are exposed on the weathered surfaces at four levels, and many of them occur on the slope surfaces after being weathered out from the outcropping rock strata as geode fields (Fig. 3d). These geodes have been eroded and detached from their host strata and deposited amongst the boulder cover.

The quartz geodes (Ghudran geodes) under study are colourless, white and rarely pale grey similar to those described from the lower Tar Member of the Upper Cretaceous Zimam Formation of Libya (Makhlouf et al. 2003). The external features include the outer shape, dimensions and morphological characteristics.

Size and shape

Representative varieties of Ghudran geodes (113 samples) were collected for detailed description of external and internal features. This formation contains geodes of different shapes,

Table 2 Shape of Ghudran geodes base on their size considering the following: *L* largest axis, *W* intermediate axis and *T* shortest axis

Total number	Spheroid $L=W=T$	Oblate spheroid $L=W>T$	Prolate Spheroid $L>W=T$
113	52	40	21
100 %	46 %	35.4 %	18.6 %

Table 3 Shape of Ghudran geodes in plan view

Total number	Plan view	
	Circular	Subcircular & Elongate
113	98	15
100 %	87 %	13 %

Table 4 Size of Ghudran geodes based on their long axis

Total number	Size of geodes (based on their long axis)				
	Very small 00–9 cm	Small 10–19 cm	Medium 20–29 cm	Large 30–39 cm	Very large 40–50 cm
113	55	23	28	6	1
%	48.6 %	20.4 %	24.8 %	5.3 %	0.9 %

ranging from small (3 cm in diameter) up to large (45 cm in diameter) spheres (Fig. 4a). Shape and size of geode is probably related to the original cavity and the dissolved material. Most of Ghudran geodes are spherical, sub-spherical, ovoid and other irregular shapes (Fig. 4b–d). Among of these shapes, the spherical forms are the most dominant.

To describe the size of Ghudran geodes, length (*L*, the largest axis) and width (*W*, the intermediate axis) measurements were taken of geodes (Blatt et al. 1972; McBride et al. 1999); thickness (*T*, the shortest axis) is also measured to obtain the 3D of each geode (Table 2). Most of the geodes are spherical or spheroidal in shape (46 %), other geodes in which length and width are nearly equal are oblate spheroids (35.4 %), but thickness is less than the width ($L=W>T$), whereas, some are characterized by prolate spheroids (18.6 %), the width and thickness of which are about equal but they are less than the length ($L>W=T$) (Table 2).

Geodes with cross-section ratios less than 1.5:1 are considered as equant (circular or spherical); others with ratios 2.5:1 are considered as elongate (prolate) (Blatt et al. 1972); whereas, geodes of intermediate dimensions 2:1 are considered subequant or subcircular (oblate). In plan view, most of Ghudran geodes are circular (87 %), whereas 13 % of geodes are subcircular and elongate (Table 3).

Ghudran geodes were also classified into five categories according to their long axis as follows: very small (00–9 cm), small (10–19 cm), medium (20–29 cm), large (30–39 cm) and very large (40–50 cm) (Table 4). The most common size is the very small (4 to 9 cm in diameter) (48.6 %), followed by the medium size 20–29 cm (24.8 %), and the small size 10–19 cm (20.4 %), whereas the large size is minor, and the very large size is rare (Table 4).

Surface features

The most common surface texture of the geodes is the rough botryoidal (brain-like) pattern which is associated with some external cracks (Fig. 4c), small concentric hollows (Fig. 4b) and mammillary ridges (Fig. 4d) occur. Most geodes show polygonal cracks (Fig. 4b) and Y-shaped cracks (Fig. 4b). The sides of the cracks are slightly curved (Fig. 4d). Polygonal cracks ranges from 4 to 6 cm across and the cracks are a few millimetres wide. Concentric circular films of 2–6 cm in diameter are developed at the outer surface of some geodes

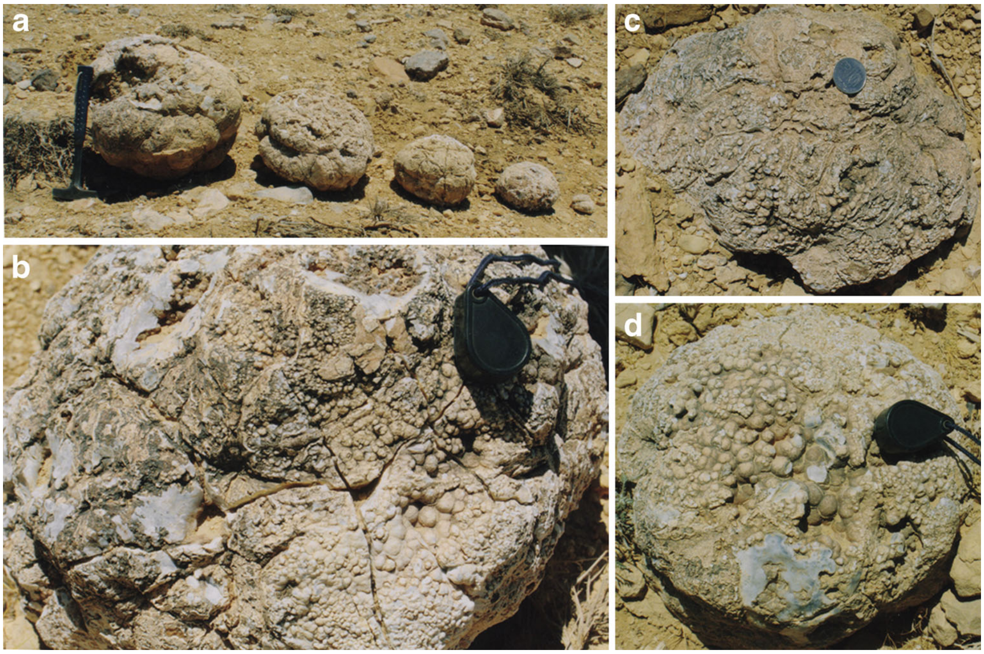


Fig. 4 Morphological features of studied quartz geodes: **a** geodes of variable sizes (hammer is 28 cm long), **b** cracked outer surface of the geode (y-shape) exhibiting multiple polygons, **c** concentric circular films at the outer surface of the geode (lens is 3 cm long), **d** rough brain-like associated with some external cracks on geode surface, **f** well-developed mammillary botryoidal growth of silica, and **g** concentric circles displaying radial pattern (coin is 2.5 cm in diameter)

(Fig. 4b, d). Some of these circular forms are enclosed within the polygonal cracks. The cracks here are tapering inward which is different than those tapering outward from the centre in the Jurassic septarian concretions described from Scotland by Hendry et al. (2006).

The more or less spherical shape of geode is controlled by the shape of the precursor-dissolved fossil or evaporite concretion and the resulting cavity; whereas, the shape of spherical nodules form where silica is supplied by diffusion, and elongate nodules form where silica is supplied by advection, the elongation develops in the direction of the fluid flow (McBride et al. 1999; Hencheri and Slim-S'himi, 2006). A concretion is often ovoid, spherical or irregular shape, hard and compact formed by the precipitation of cement in the pore space between grains (Table 5). The different textures recognized and their arrangement indicates the development of the diagenetic processes responsible for the formation of geodes.

Interior description

Geodes are partially or completely infilled with crystalline (Fig. 5 a–d) or granular (botryoidal) with outer cryptocrystalline silica (chalcedony) (Fig. 5b). The majority of the geodes regardless of their morphology display visible zoning of concentric structure defined by a succession of different types of quartz textures and phases. Quartz geodes normally have a rind 5–10 mm thick of more resistant chert. The light brown colour is imparted by a thin layer of desert varnish that forms on the external surface of the geodes. Some geodes have a few millimetres wide with pale grey outer rim of chalcedony (Fig. 5b). The quartz filling is white, colourless and purplish colour. The inward-projecting quartz crystals are euhedral (Fig. 5c), subhedral and anhedral forms. White cryptocrystalline silica (chalcedony) mantles the outer wall of the geode and attains a thickness of a few millimetres crust to half or more of the thickness of the geode (Fig. 5c, d). Bands within some geodes have discordances that reflect uneven or interrupted growth patterns (McBride et al. 1999).

Occasionally, chalcedony grows throughout the void until complete filling of some geodes (Fig. 5d). In these examples, massive, dense, heavy and very hard geodes are produced (Fig. 5d). The granular cluster silica represents the anhedral and amorphous forms of silica (Fig. 5a). As a result, two types of geodes were recognized; hollow geodes (Fig. 5a,b) and massive geodes (Fig. 5d).

Megaquartz occurs as single euhedral crystals associated with subhedral crystals (Fig. 5a–c) ranging in size from parts of millimetre to 3 mm across. Most of the euhedral crystals are of hexagonal bipyramidal shape.

Mineralogy and geochemistry

Mineral and chemical analysis of major and trace constituents using the SEM (BSE and SEI) are illustrated (Table 6, Fig. 6a–c). Spot analysis indicates that the geodes composed totally of Si and O with traces of Al (0.05 %), whereas line scan indicated presence of other interstitial phases containing Al (0.47 %) and K (between 0.03 and 0.68 % by wt) such as clay minerals. Chemical impurities in the quartz phase are between 0.11 and 1.44 % (Table 6). Presence of Cl (up to 0.29 %) could be related to rock-water interactions (Panno et al. 2000).

Investigations of the quartz microstructure by SEM showed that the quartz crystals may have formed by crystallization from the same silica source. Absence of defects or zoning at the internal structures of the quartz, as shown by the SEM-BSE, may indicate that crystallization went slowly under equilibrium conditions (Florke et al., 1991). The SEM in Fig. 7a–d reveal that most of the quartz in the geodes can be called macro-quartz as they have grains larger than 50 μm

Table 5 Comparison between quartz geodes and quartz concretions (nodules) after various sources

	Quartz geodes	Quartz nodules (concretion)
1	Macrocrystals in addition to microcrystals and chalcedony.	Only microcrystalline and chalcedony crystals.
2	Commonly partially filled.	Always completely filled.
3	Growth from out to centre.	Growth from centre to outside.
4	Precipitation after long time.	Replacement during diagenesis.
5	Shape depends on the original cavity.	Shape depends on the solution movement.
6	Zonation shows different quartz textures; micro- and macrocrystalline.	Zonation shows similar films of microcrystalline quartz.
7	Geodes are always solitary.	Occasionally small nodules are enclosed in larger nodules.
8	Inclusions are totally absent.	Inclusions of relic components and ghosts of the host sediments may be present.
9	Nuclei are absent.	Nuclei are common; some concretions have grown around fossil nuclei.
10	No flat bases or tops. Constrained with the shape of cavity boundary.	Some show flat bases and tops.
11	Commonly with internal concentric structures.	With or without internal concentric structures.

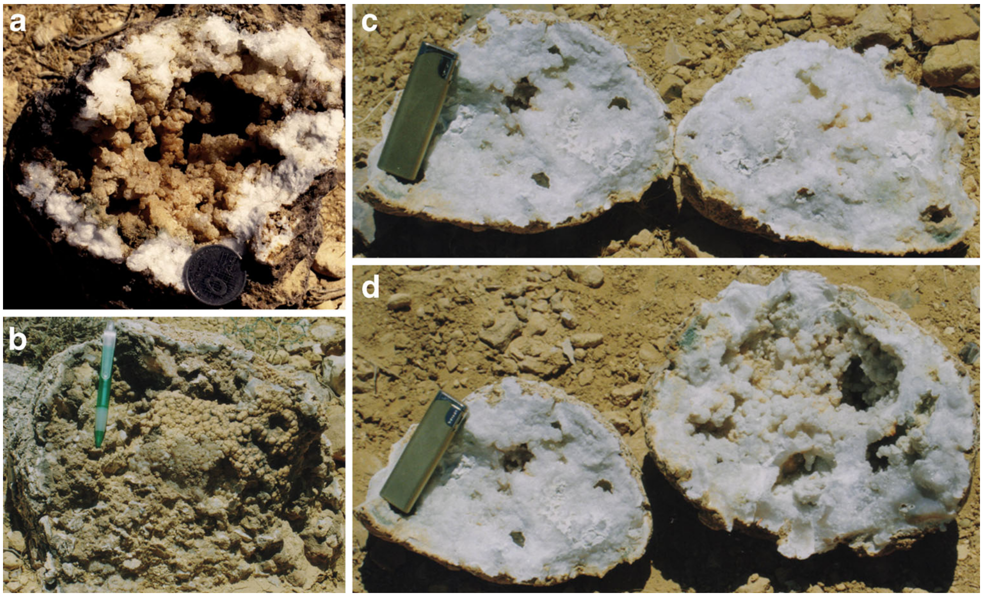


Fig. 5 Broken-open geodes showing type of filling: **a** vacuum geode showing arrangement of outer chalcedonic layer and inner well-developed crystals (coin is 2.5 cm in diameter), **b** chalcedonic outer layer and well-developed internal crystal forms associated with granular cluster (mammillary) features (pencil is 15 cm long), **c** cryptocrystalline in massive vacuum geode, and **d** massive vacuum geode (lighter is 4 cm long)

based on Florke et al. (1991). The present study utilized electron backscatter patterns (BSE) to assess the crystallinity of individual points in the lattice overgrowths. The pronounced zone axis and strong image present in Fig. 8 indicates that the quartz grains are well crystalline. Lack of crystallographic complexities associated with disordered microcrystalline quartz in the studied samples manifest well-defined crystals (Knauth 1994). It forms prismatic crystals (Fig. 7c,d) which are typically elongated parallel to the *C*-axis. Most of the crystalline quartz has equidimensional hexagonal crystal shape displaying a positive refractive index that is determinable using optical microscopy (Hesse 1989; Heaney et al. 1994).

Geode genesis

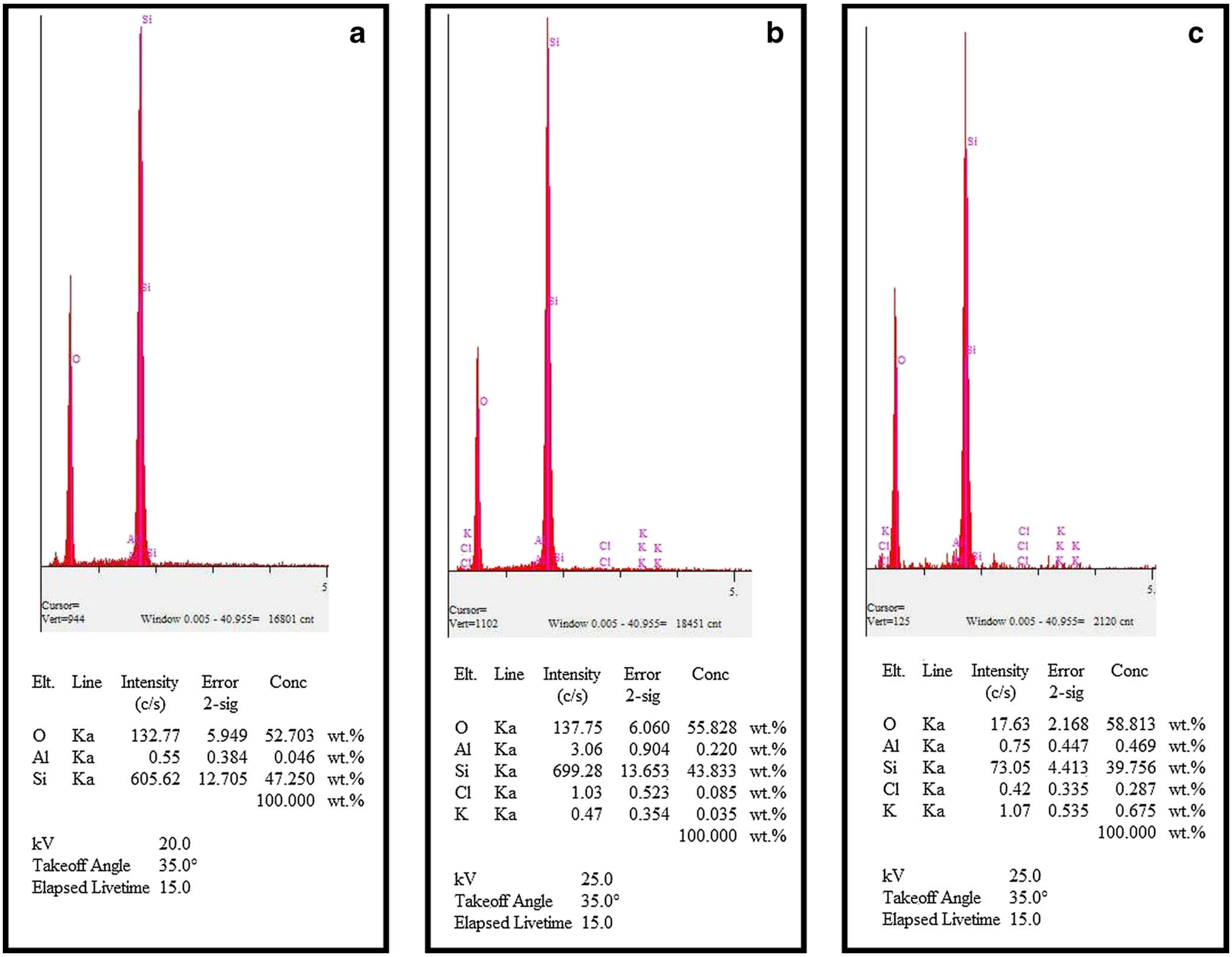
The occurrence of geodes in four stratigraphic levels in the study area reflects a suitable textural lithology for geode growth, or the occurrence of local source of silica (McBride et al. 1999). Geode morphologies are almost similar spherical forms, but other irregular morphologies are not uncommon; and their diversity presents considerable interpretative difficulties and creates discussions as to whether or not some geodes may represent the sites of shells of bivalves, echinoids or coral which are completely dissolved during diagenesis (Bassler 1908; Makhlouf et al. 2003). The original cavity in which geode was developed may give an indication of the precursor organism or mineral that has been dissolved prior to their subsequent formation.

The formation of geodes is still scientifically unconfirmed, but the deposition of silica gel and fluctuating water table are important factors. Robertson (1944, 1951) suggested that geodes were syngenetically deposited on the sea floor as colloidal masses of hydrated silica, and that the later loss of water from the gel produced the chalcedonic shell.

Hayes (1964) presumed that the precursors of geodes were calcareous concretions rather than silica gel, which is concordant with a view earlier expressed by Van Tuyl (1916). Pettijohn (1975) reviewed the ideas of earlier workers, indicating that Bassler (1908) was the first to show that many geodes originate from fossils such as crinoid calyx, or a bivalve, etc. It is believed that the formation of geodes took place after a complete dissolution of the pre-existing organisms and the infiltration of silica-rich solutions. Prothero and Schwab (1996) believed that some sort of void must first exist in the host rock such as a hollow cavity of a fossil, where a mass of gelatinous silica collects in the void and begins to crystallize in concentric layers around the rim. This is true for some geodes as those described from Libya by Makhlouf et al. (2003), where clear evidence of a fossil origin based on the shape of pre-existing fossils; but in the present case; this

Table 6 Microelements chemical analyses in weight percent of the geodes using SEM-EDS method

Sample No	Si	O	Al	K	Cl	Total	Object of study
1	47.25	52.70	0.05			100.00	Spot scan in quartz
2	39.75	58.81	0.47	0.68	0.29	100.00	Line scan in quartz
3	43.90	55.90		0.03	0.09	99.92	Line scan in quartz



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Elt.  Line  Intensity   Error    Conc
            (c/s)       2-sig

O     Ka    132.77      5.949    52.703  wt.%
Al    Ka      0.55      0.384     0.046  wt.%
Si    Ka    605.62     12.705    47.250  wt.%
                                100.000  wt.%

kV                20.0
Takeoff Angle     35.0°
Elapsed Livetime  15.0
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Elt.  Line  Intensity   Error    Conc
            (c/s)       2-sig

O     Ka    137.75      6.060    55.828  wt.%
Al    Ka      3.06      0.904     0.220  wt.%
Si    Ka    699.28     13.653    43.833  wt.%
Cl    Ka      1.03      0.523     0.085  wt.%
K     Ka      0.47      0.354     0.035  wt.%
                                100.000  wt.%

kV                25.0
Takeoff Angle     35.0°
Elapsed Livetime  15.0
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Elt.  Line  Intensity   Error    Conc
            (c/s)       2-sig

O     Ka     17.63      2.168    58.813  wt.%
Al    Ka      0.75      0.447     0.469  wt.%
Si    Ka     73.05      4.413    39.756  wt.%
Cl    Ka      0.42      0.335     0.287  wt.%
K     Ka      1.07      0.535     0.675  wt.%
                                100.000  wt.%

kV                25.0
Takeoff Angle     35.0°
Elapsed Livetime  15.0
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Fig. 6 SEM-EDS spot and line scan in the selected geode samples. **a** SEM-EDS spot scan in quartz grain illustrates the major elements distribution in the geodes. **b, c** SEM-EDS line scans, through the quartz grains illustrates the major elements distribution

theory does not seem to fit because there is no evidence for dissolution of precursor fossils.

Geodes in sedimentary rocks are developed when the ground water carrying dissolved minerals seeps into these hollows; the minerals crystallize on their inner surface to produce a round hard covering consisting of extremely fine-grained quartz (chalcedony). These hollows remain full of mineral-rich water or get filled again when the water table rises then re-depositing of mineral water forms the crystalline structures over a very long period of time. As time passes and more minerals are deposited, new layers of hexagonal-shaped crystals grow on old until the whole cavity is almost filled with inward-projecting hexagonal quartz crystals. In other cases, the cavity may be hollow and partially filled with a complex intergrowth of large and small crystals. Vacuum geode is probably the result of low supply rate of fluids bringing silica into rock cavities and/or the physico-chemical conditions of the fluids responsible for precipitation (Woo et al. 2008). This slow displacive theory seems to be the most likely for the development of the Ghudran geodes.

Fischer et al. (2010) shown that the geodes of Serra Geral Formation in Brazil exhibit the same sequence of silica infilling from outer wall to centre of the cavity: chalcedony rim, colourless quartz crystals increasing in size inward, and finally amethyst. Therefore, the most recent crystallization develops towards the centre of the geode. The cavity is filled with interlocking crystals if the crystallization is complete, and in this case the geode becomes heavy, solid and massive. Occasionally, some geodes that are completely filled have an inner layer of agate surrounded by hexagonal crystals caused by a silica gel that got through the chalcedony and later dried (Fischer et al. 2010).

Maliva and Siever (1988) indicated in their model that the diagenetic replacements involve two processes: (1) the dissolution of the mineral phase that is being replaced (host phase) and (2) the precipitation of an authigenic mineral phase. Some

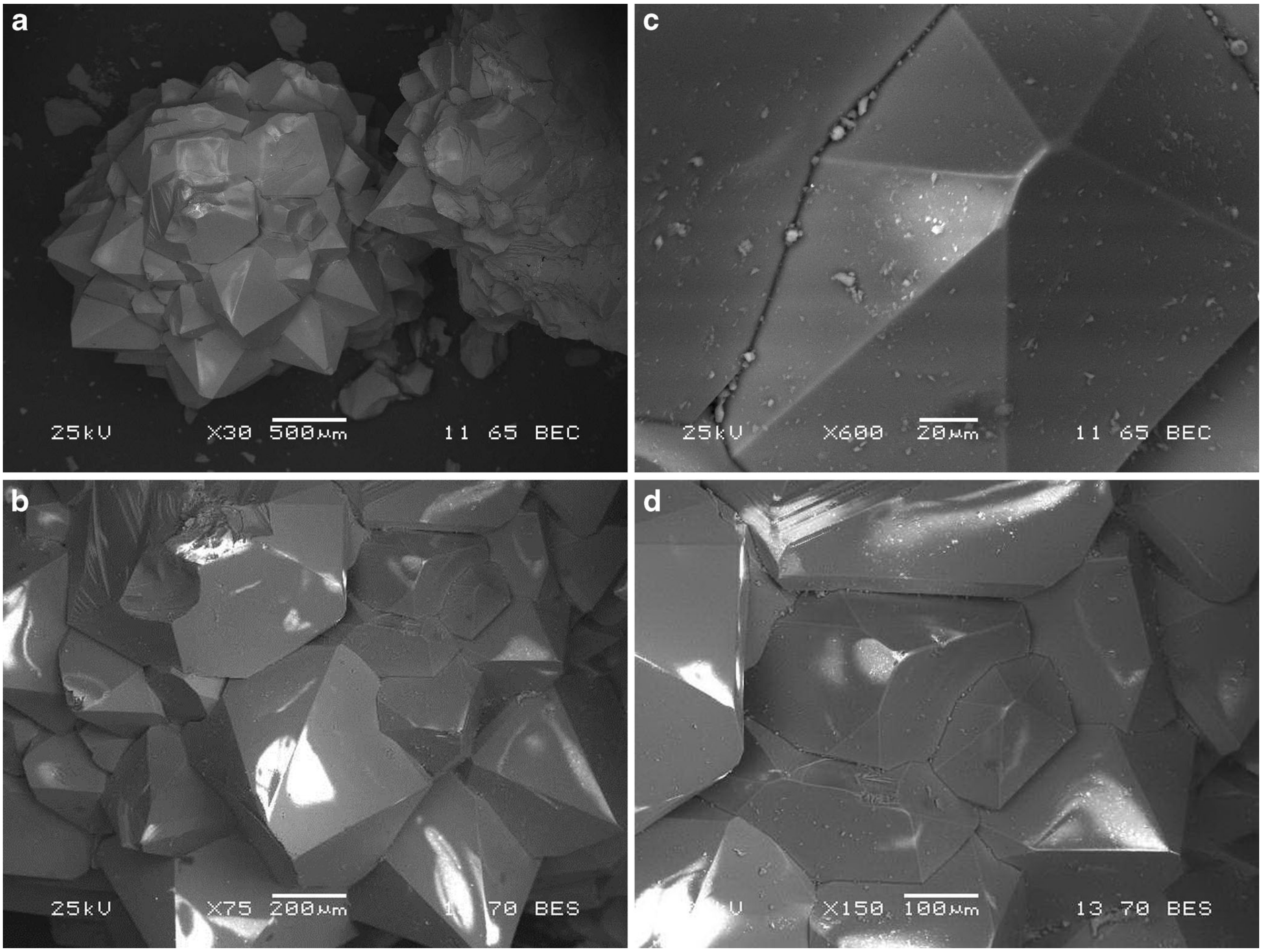

Fig. 7 Micrograph of SEM- BSE from individual quartz grains: **a** Micrograph of strong SEM-BSE for segregation or cluster of crystalline quartz; **b** Micrograph of SEM-BSE of well-developed crystalline quartz; **c** Micrograph of SEM-BSE of hexagonal well-developed crystalline quartz; **d** Micrograph of SEM-BSE showing well-developed coarse crystalline quartz grains

cherts are diagenetic formed by replacement of another mineral by water rich in silica flowing through the rock; they commonly replace limestones to form nodules or irregular layers (Nichols 1999).

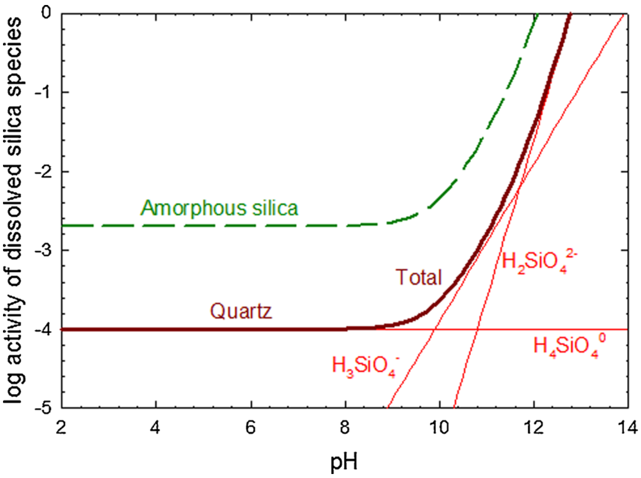

Fig. 8 Silica solubility in natural environment from Kehew (2001)

Makhlouf et al. (2003) showed that the nature of the original cavity is predicted from the external shape of some geodes of the Cretaceous Tar Member of Libya, when they compared some fossils with their counterpart geodes of close resemblance in size, shape and surface features. However, it is not always possible to relate geodes to their original organic cavities because of the probable incomplete dissolution of the original shell or the partial dissolution of the host rock around the shell body which enlarge and distorts the original cavity (Bassler 1908; Makhlouf et al. 2003). Elorza and Rodriguez-Lazaro (1984) reported that cauliflower-like quartz geodes of the Late Cretaceous in Spain were formed during early diagenesis as pseudomorphs of anhydrite nodules. This is the most likely origin for the Ghudran geodes. There is plenty of evidence in the literature for precursor minerals to be anhydrite and or gypsum nodules (Powell and Moh'd 2011, 2012). This also seems more likely in the Ras en Naqb area which contains shallow water chalky, sandy and marly sediments when compared to the deeper water pelagic and hemi-pelagic settings in Wadi Mujib farther north, that lay more basinwards in Coniacian to Santonian times (Powell and Moh'd 2011, 2012). The presence of silicoflagellates and radiolarian in these sediments is probably the original source for the silica/opal-CT that has replaced original anhydrite/gypsum nodules during early to late diagenesis ((Powell and Moh'd 2012).

Hein and Parrish (1987) indicated that the global production and preservation of siliceous deposits has been relatively high since the Jurassic, peaking during the Cretaceous and Palaeogene, and the chert is not evenly distributed by latitude but has a strong peak distribution between 0 and 30 palaeolatitude.

Source of silica

The basic steps of the geochemical cycle include dissolution of minerals, transportation and precipitation. In these conditions, silica is a major constituent of many solids and of prime importance. According to Kehew (2001), silica solubility is relatively low and dependant of pH at $\mathrm{pH}<9$ where $H_4SiO_4{}^0$ is the dominant species. Silica solubility increases with increasing pH above 9, where $H_3SiO_4{}^-$ and $H_2SiO_4{}^{2-}$ are dominant (Fig. 8). Fluoride, and possibly organic compounds, may increase the solubility of silica (Kehew 2001), whereas increased concentration of sodium chloride, sodium sulphate, magnesium chloride and magnesium sulphate depress silica solubility (Chen and Marshall 1982).

In Jordan, origin of silica solution was studied by Khoury (1986, 1987) to explain the origin of the widespread tripolization process in the silicified limestone beds of the Upper Cretaceous. He concluded that tripolization is a substitutional process by pH fluctuations, where silica-rich solutions replaced the limestone beds (Khoury 1986). The origin of hyperalkaline environment according to Clark et. al. (1994) is the in situ spontaneous combustion of bituminous marl in the overlying formation that has led to calcination and formation of calcium/silica/alumina-oxides. The high pH ground waters interact with the surrounding limestones and marls. In other parts of the country, the high pH seepages precipitate travertines as a result of the uptake of atmospheric CO_2 (Khoury 1997). This source of silica is not relevant to the present study area because the thermo-metamorphic event only occurred in central Jordan where organic shales underwent thermal combustion. This did not occur in South Jordan because these deeper water anoxic Maastrichtian sediments were not deposited in the shallower conditions prevailed south (Powell and Mohd, 2012).

Dietzel (2000) indicated that the source of silicic acid in natural weathering environment is the transformation and dissolution of silicates minerals. Quartz is formed diagenetically through the following sequence of reactions: silicic acid → opal-A → opal-CT → chalcedony → microcrystalline quartz (Flörke et al. 1991). Therefore, silica-rich solutions (silicic acid) in the study area can be derived from the chemical weathering of tripoli, tripolized chert and clay minerals associated with the Wadi Umm Ghudran Formation and from the overlying Amman Silicified Limestone Formation. The chemical products increase the degree of silica-saturated solutions, and by the chemical action of percolating and groundwater could infiltrate into the underneath host rock (Umm Ghudran Formation) through pores and fissures, to occupy the cavities of the pre-existing fossils, where it precipitated and crystallized to form geodes. The chemical action of groundwater may dissolve clay minerals thereby adding to the percent of silica-saturated water. The movement of silica-saturated water through joints, fissures, faults and pore-spaces may be responsible for the concentration into rock cavities, and further precipitation and formation of geodes.

An organic source of silica also seems most likely possible, especially in marine environments rich in radiolarians which are liable to be destroyed and dissolved under alkaline conditions. Diatoms are also an important source of silica which accumulates in sediments in a great variety and in enormous numbers. Siliceous organisms could increase the silica percentage in marine water. The infiltration of such solutions into the cavities of the underlying rocks may produce geodes. The opal-A further changes to opal-CT and chalcedonic quartz during diagenesis (Nichols 1999). The source of the silica is almost certainly the remains of siliceous organisms deposited with the calcareous sediment (Calvert 1974; Tucker 1991). Sponge spicules were the principal source of silica for the development of the quartz geodes and chert nodules of the Late Cretaceous that formed during early diagenesis of anhydrite nodules in Spain (Elorza and Rodriguez-Lazaro 1984). In Ghudran geodes, radiolarian and silicoflaggelates seem a more plausible source of silica, as the sponge spicules were not recorded in the Jordanian sediments.

The phase transitions between the silica polymorphs are complex, with a number of polymorphs present at the same time, resulting in complicated mineralogical and textural patterns at the microscale (Herdianita et al. 2000). Ideally, only one polymorph of silica can be present at one time; however, kinetics and rates of transformation among the polymorphs are slow enough for metastable polymorphs to exist (Williams et al. 1985). Stamatakis et al. (1991) noted factors which affect the diagenetic transformation of non-crystalline opal-A through to microcrystalline quartz: burial depth, time, heat flow and host rock lithology. It can be argued that the results of SEM indicate such diagenetic transformation in our samples which is supported by increasing degree of crystallinity of quartz grains inside the geodes.

Conclusions

Most of the quartz geodes are well developed in the fossiliferous beds of the Umm Ghudran Formation, and the dissolution of possible fossils and other nodules and concretions (anhydrite and gypsum) provide the pre-requisite initial cavities for the formation of geodes (Bassler 1908; Maliva and Siever 1988; Makhlouf et al. 2003). The infiltration of silica-rich solutions into these cavities, the dehydration of siliceous solutions and precipitation of silica gel form an outer chalcedonic layer mantling the cavity wall for cavity mould preservation.

The crystallization of the remaining solution as a drusy lining over the chalcedonic layer as euhedral, subhedral, anhedral crystal forms, or as seedy clusters could occasionally posses a cotton-like appearance. The precipitation of silica could leave a space in the cavity or could fill it completely leaving no space. It is also concluded that the spherical, sub-spherical or irregularly shaped geodes can be related to the original dissolved nodules or other forms and concentric films lining the outer surface of some geodes. Spot analysis indicates that the geodes composed totally of Si and O with traces of Al (0.05 %). Investigations showed that the crystallization went slowly under equilibrium conditions and formed from the same silica source.

Acknowledgements The authors are grateful to the Hashemite University and the Natural Resources Authority for providing logistic support during the field work. Special thanks to John Powell from the BGS for his helpful comments and careful reading of the manuscript. Mohammed Abdelghafour is thanked for drawing some of the figures. Al Hussein Bin Talal University is thanked for offering the research facilities including scanning electron microscope, and Eng. Ahmed Al Harases is thanked for SEM photography. We also thank two anonymous reviewers who have significantly improved this paper.

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