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New insights into the genesis of the Miocene collapse structures of the island of Gozo (Malta, central Mediterranean Sea)

J. P. Galve[1]*, C. Tonelli[2], F. Gutiérrez[3], S. Lugli[2], A. Vescogni[2] & M. Soldati[2]

[1] Departamento de Geodinámica, Universidad de Granada, Campus de Fuentenueva s/n, 18071 Granada, Spain
[2] Dipartimento di Scienze Chimiche e Geologiche, Università di Modena e Reggio Emilia, Largo S. Eufemia 19, 41121 Modena, Italy
[3] Departamento de Ciencias de la Tierra, Universidad de Zaragoza, C/Pedro Cerbuna 12, 50009 Zaragoza, Spain
* Correspondence: jpgalve@ugr.es

Abstract: The large palaeosinkholes located in the NW of Gozo (central Mediterranean Sea, Malta) offer excellent exposures that provide information on the geometry and kinematics of large karst-related collapse structures. Detailed geological analysis of these peculiar palaeosinkholes indicates that deep-seated evaporite dissolution is the most feasible hypothesis to explain their formation, according to the following evidence. (1) Several structures have been formed by progressive foundering of cylindrical blocks with limited internal deformation as revealed by the synsedimentary subsidence recorded by their Miocene sedimentary fill. This subsidence mechanism is more compatible with interstratal dissolution of evaporites than karstification and cave development in limestone formations. (2) The dimensions and deformation style of the palaeosinkholes are similar to those of other collapse structures related to deep-seated dissolution of salt-bearing evaporites. (3) The arcuate monocline associated with some of these collapse structures is also a characteristic feature of subsidence related to dissolution of evaporites. However, no major evaporite formations have been documented so far in the subsurface of the Malta Platform.

Supplementary material: Detailed descriptions of the collapse structures of the island of Gozo (Malta, central Mediterranean Sea) are available at www.geolsoc.org.uk/SUP18808.

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Giant collapse sinkholes are one of the Earth's most dramatic and enigmatic landforms. Well-known examples include the Tiankengs of China and SE Asia, which reach several hundred metres deep and across (Waltham 2006), the Obruks of Central Anatolia (Bayari *et al.* 2009), the large collapse dolines of the Dinaric karst (e.g. Crveno Jezero, Garašić 2000; Velika Dolina, Waltham 2006), and the Zacatón sinkhole in Mexico (Gary & Sharp 2006). Large collapse palaeosinkholes have been preserved in the geological record as gravitational deformation structures (e.g. ring faulting, breccia pipes) and related sedimentary features (e.g. sinkhole fills, local thickness variations, cumulative wedge-outs). These features have been described in the Colorado Plateau, USA (Weir *et al.* 1961; Cater 1970; Sugiura & Kitcho 1981; Gutiérrez 2004), southern Saskatchewan, Canada (Christiansen 1971; Gendzwill & Hajnal 1971; Christiansen & Sauer 2001), NE Spain (Gutiérrez 1996, 2014) and southern Hunan, China (Min *et al.* 1997). Large collapse palaeosinkholes have also been identified through 3D seismic surveys in sedimentary basins of southern Australia (Brown 1999), Venezuela (Castillo & Mann 2006), the USA (McDonnell *et al.* 2007), the Mediterranean Sea (Bertoni & Cartwright 2005; Lofi *et al.* 2012) and the South China Sea (Sun *et al.* 2013).

These structures have a multidisciplinary importance because their identification aids in ore and hydrocarbon exploration in sedimentary basins affected by deep-burial dissolution processes. Fossil collapse sinkholes are markers of large-scale deep-seated karstification that favoured the migration and/or accumulation of hydrocarbons in the Maracaibo basin, Venezuela (Castillo & Mann 2006), in the Fort Worth basin, Texas, USA (McDonnell *et al.* 2007), and in the South China Sea basin (Sun *et al.* 2013). Palaeosinkhole-hosted uranium deposits of a high economic importance have been exploited in China (Min *et al.* 1997) and Arizona, USA (Wenrich & Titley 2008). Sun *et al.* (2013) highlighted that deep-burial dissolution should be taken into account when assessing reservoir heterogeneity and infrastructure risks in the largest offshore oilfields. This also applies to the evaluation and exploitation of ore deposits associated with palaeosinkholes. However, to our knowledge, studies on palaeosinkholes that may help to characterize deep-seated dissolution environments are very scarce. Detailed analyses on well-exposed large collapse structures, paying attention to their geometry, internal structure, kinematics and origin, are needed to better understand similar structures and geomorphological features identified by indirect methods in the subsurface or in the sea floor.

The large palaeocollapse sinkholes of Gozo, Malta, central Mediterranean, described by Pedley (1974), are revisited in this paper. They offer excellent exposures that allow direct information to be obtained on the internal architecture and kinematics of large karst-related collapse structures developed on the sea floor. In some cases, they display spectacular landforms of high scientific and scenic value, which deserve protection and conservation measures (Coratza *et al.* 2012). Previous studies, dating back to the 1970s and 1980s, analysed these fossil collapses from a sedimentological perspective (e.g. Pedley & Bennet 1985). Their main interest was that these palaeosinkholes acted as sediment traps favouring the preferential accumulation of detrital phosphorites. Other aspects, such as their structural style and origin, have not been analysed in depth by previous researchers, although Soldati *et al.* (2013) undertook a geomorphological study. Detailed examination and mapping of structural and stratigraphic features documented in the present study contribute to shed some light on their debatable origin. These large collapse features have been previously attributed to the breakdown of a cave system developed in limestone (Pedley 1974) or to deep-seated evaporite dissolution (Illies 1980; Pedley *et al.* 2002). The aim of this paper is to discuss these theories and the possible

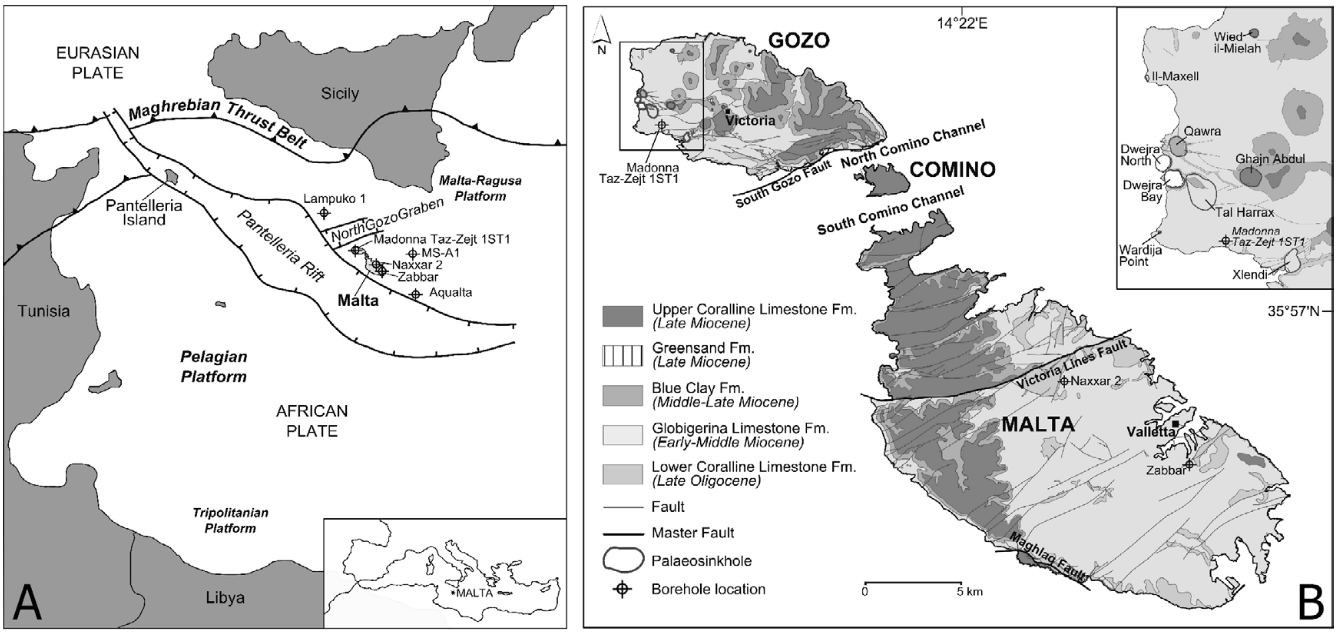

Fig. 1. (**a**) Sketch showing the geotectonic setting of the Maltese archipelago, and the main deep boreholes drilled in and around the islands. (**b**) Simplified geological map of the Maltese archipelago showing the distribution of stratigraphic units and faults, as well as the palaeosinkholes of Gozo. On the right, close-up of the NW sector of Gozo with the names of the collapse structures analysed in this study.

karstification and subsidence mechanisms responsible for their development. We have collected and analysed novel data regarding the following aspects: (1) regional geological and stratigraphic context; (2) stratigraphic and structural relationships observed in detailed geological maps; (3) stratigraphic and sedimentological features of the sediments deposited in the submarine sinkholes; (4) biostratigraphic data inferred from planktonic foraminifera; (5) bathymetric data and geomorphological evidence of probable residual activity. This information allows us to infer aspects related to the development of the sinkholes, including the deformation style, the spatial association with other structures of probable gravitational origin, the kinematics of the subsidence and its duration. The discussion on the possible genetic alternatives for the palaeosinkholes takes into account the new knowledge frame and a number of large dissolution-induced collapse structures documented worldwide.

Geological setting

The Maltese archipelago is located in the central Mediterranean Sea, around 90 km south of Sicily and 290 km east of Tunisia (Fig. 1a). It consists of three main islands: Malta (246 km^2), Gozo (67 km^2) and Comino (3.5 km^2) (Fig. 1b). From the geotectonic perspective, the archipelago is located in the northern African plate, and more specifically on the Pelagian Platform, a continental shelf between southern Sicily (Malta–Ragusa platform) and northern Libya (Tripolitanian platform) (Illies 1981; Fig. 1a). These platforms constitute the foreland of the south-verging Maghrebian Thrust Belt, at the collision zone between the Eurasian and African plates. The Pelagian Platform is cut by the deep NW–SE-trending trough of the Pantelleria Rift. The northeastern part of the rift is designated as the Malta Graben (Gardiner *et al.* 1995). The Maltese archipelago is located on the NE shoulder of the Pantelleria Rift, very close to the master fault that controls the graben margin escarpment (Fig. 1a). Around 10 km NW of the island of Gozo is an ENE–WSW-oriented graben, called the North Gozo Graben. This structure is controlled by oblique dextral-normal faults that connect with the normal faults of the Pantelleria Rift (tear faults). The kinematic evolution of these structures has been inferred by Gardiner *et al.* (1995) on the basis of stratigraphic and structural relationships observed in seismic profiles (e.g. thickness variations and offset sedimentary units). The Pantelleria Rift began to open in late Miocene to mid-Pliocene time under an extensional regime. The formation of the North Gozo Graben started in the late Pliocene, in relation to a change in the tectonic regime, from simple extension to right-lateral transtension. The oblique dextral faults with vertical components that control the North Gozo Graben offset in Pleistocene sediments and the sea floor, strongly suggesting that they correspond to an active fault system (Gardiner *et al.* 1995).

The rocks exposed in the islands comprise a Late Oligocene (Chattian) to Late Miocene (Messinian) marine sedimentary succession mostly composed of limestones and marls (Fig. 1b). Five lithostratigraphic units form the outcropping sequence (Oil Exploration Directorate 1993; Pedley *et al.* 2002). The lowermost exposed unit is the Lower Coralline Limestone Formation (Chattian) of pale grey, hard, shallow marine biomicrites and biosparites around 140 m thick. The following units, in ascending order, are as follows: (1) the Globigerina Limestone Formation (Aquitanian–Langhian, a yellowish, fine-grained, planktonic foraminiferal limestone, 20 m to over 200 m in thickness; this formation has been subdivided into three members by the occurrence of laterally extensive phosphorite conglomerate beds (i.e. Lower and Upper Main Phosphorite Conglomerate Beds; Pedley & Bennet 1985); (2) the Blue Clay Formation (Serravallian–Tortonian), which consists of grey, soft marls, clays and silty sands 20–70 m thick; (3) the Greensand Formation (Tortonian), which is brown and greenish, glauconite-rich and generally less than 1 m thick, but reaching 11 m thick; (4) the Upper Coralline Limestone Formation (Tortonian–Messinian), which is broadly similar to the Lower Coralline Limestone Formation and up to 160 m thick.

The unexposed stratigraphic units beneath the Late Oligocene Lower Coralline Limestone Formation were shown by the BP oil exploration borehole (Naxxar 2) on the island of Malta (Fig. 1b). It revealed a 3000 m thick sequence of platform carbonates, mainly dolomites, dating back to the Early Cretaceous in its lowermost part (Pedley 1990). Extensive dissolution-related cavernization was found within the Tertiary and Mesozoic carbonate strata in this borehole (Pedley 1974). Another borehole drilled offshore by the Shell company (MS-A1 borehole; Fig. 1a) 40 km NE of the island of Malta shows a similar dolomite succession 5000 m thick down to the Lower Jurassic (Jongsma *et al.* 1985). The Madonna

Table 1. *Parameters for the nine selected palaeosinkholes of western Gozo*

Name	Major axis (m)	Minor axis (m)	Elongation ratio	Area (m^2)	Throw (m)	Volume of dissolved karst rocks (hm^3)	Youngest sediments displaced	Distance to the nearest collapse (m)	Horizontal offset on cross-cutting tectonic faults (m)	Geomorphological expression
Qawra	368	365	1.01	110085	>60	>6.61	Blue Clay	75	46	Depression
Tal Harrax	596	556	1.07	325064	*c.* 100	>16.25	Blue Clay	30	16	Depression
Xlendi	330	278	1.19	112171	>50	>6.17	Globigerina Limestone	1600		Depression
Dwejra North	337	311	1.08	82088	>40	>3.28	Globigerina Limestone?	38	–	Bay
Dwejra Bay	380	351	1.08	120762	>40	>4.83	Globigerina Limestone?	30	16	Bay
Il-Maxell	>120	>120	?	?	>15	?	Globigerina Limestone	1290	–	Depression
Ghajn Abdul	440	371	1.18	130575	>50	>6.53	Upper Coralline Limestone	550		Mesa
Wardija Point	65	48	1.35	2497	>50	>0.12	Upper Coralline Limestone	845	–	Butte
Wied il-Mielah	181	176	1.03	24389	>60	>1.46	Upper Coralline Limestone	2180	–	Butte

1 hm^3 is $1 \times 10^6 m^3$.

Taz-Zejt 1ST1 borehole, drilled on land in western Gozo (Fig. 1), proved a 3200 m thick Late Triassic succession from a depth of 4.5 km, consisting of dolomites, shales and metres-thick anhydrite beds, the last with an aggregate thickness of *c.* 230 m (Debono *et al.* 2000). In Zabbar and Aqualta boreholes, drilled in the Malta Platform (Fig. 1a), a 1 m thick gypsum bed has been recorded at the Eocene–Oligocene boundary, 100–150 m below the base of the Lower Coralline Limestone (Gatt & Gluyas 2012).

Overall, the geological structure of the Maltese archipelago is characterized by subhorizontal or gently dipping Tertiary successions offset by different high-angle fault systems. The NW–SE-trending Maghlaq Fault, on the southwestern edge of the island of Malta (Fig. 1b), is the main exposed normal fault related to the Pantelleria Rift, which is mostly located offshore to the SW of the archipelago (Illies 1980; Fig. 1a). The general gentle NE dip of the Tertiary strata in the archipelago is attributed to upwarping and backtilting on the NE shoulder of the Pantelleria Rift (Illies 1980, 1981; Grasso & Pedley 1985). An ENE–WSW-trending graben system around 15 km wide extends from southeastern Gozo to the central sector of Malta, including Comino and the straits between the three islands. This extensional structure, which is oblique to the adjacent Pantelleria Rift, is bounded by the North Comino Channel Fault (or South Gozo Fault of Grasso *et al.* 1986) to the north, and the Victoria Lines Fault to the south (Illies 1980; Fig. 1b). The graben shows a concordant topography with a succession of flat-topped ridges (horsts) and valleys (grabens) controlled by ENE–WSW secondary normal faults. According to Gardiner *et al.* (1995), these originally normal faults may have been reactivated as dextral strike-slip faults during the Plio-Pleistocene, concurrently with the development of the North Gozo Graben.

In the western sector of Gozo there is a system of east–west oblique-slip normal faults. Some of these faults offset vertically and laterally the annular collapse structures analysed in this study (Illies 1980; Oil Exploration Directorate 1993). Most probably, this fault system is related to the development of the adjacent North Gozo Graben since the late Pliocene, which shows evidence of recent faulting consistent with a right-lateral transtensional regime (Gardiner *et al.* 1995). This is a unique example in which dissolution collapse structures may be used as a structural marker to identify and assess neotectonic deformation.

Palaeosinkhole characteristics

The island of Gozo has 13 mapped collapse palaeosinkholes controlled by subvertical dip-slip faults with a circular to elliptical cartographic trace (Pedley 1974; Illies 1980; Oil Exploration Directorate 1993; Soldati *et al.* 2013; Fig. 1b). We analysed nine of the largest structures, mostly located in the western coastal sector of the island. Parameters including their size, geometry, amount of vertical displacement, subsurface dissolution and relative spatial distribution are shown in Table 1. Some palaeosinkholes reach exceptionally large dimensions ranging from 65 to 600 m and most of them have a nearly circular geometry. The sizes of the palaeosinkholes generally decrease in area towards the NE. The minimum vertical offset values range from >15 to >60 m. The minimum cumulative dissolution volume for the eight palaeosinkholes with data is 45.25 hm^3, roughly equivalent to a cube with an edge of 360 m. The actual subsurface dissolution volumes may be substantially larger than the estimated ones owing to the following factors: (1) the structural throw used in the calculations is a minimum value; (2) although strongly affected by dissolution, some stratigraphic levels may have not collapsed; (3) the foundered sediments may have brecciated and increased their volume by gravitational deformation owing to the bulking effect (Gutiérrez & Cooper 2013).

The Upper Coralline Limestone is the youngest stratigraphic unit affected by the collapse structures. No deformed Quaternary deposits or landforms have been identified on land associated with the faults bounding the palaeosinkholes. Quaternary stratigraphic and geomorphological markers at the margins of the collapse structures are scarce. These data suggest that at least some of the structures have been active some time after the deposition of the Late Miocene (Tortonian–Messinian) Upper Coralline Limestone, and that later they may have been inactive or had a low subsidence rate.

Some collapses are offset by oblique-slip normal faults with strikes varying from ENE–WSW to ESE–WNW. The subvertical collapse faults have been displaced horizontally by these tectonic faults by as much as 46 m (Qawra palaeosinkhole) (Table 1). This evidence suggests that the oblique-slip faults are younger than the gravitational collapse faults (post-Upper Coralline Limestone).

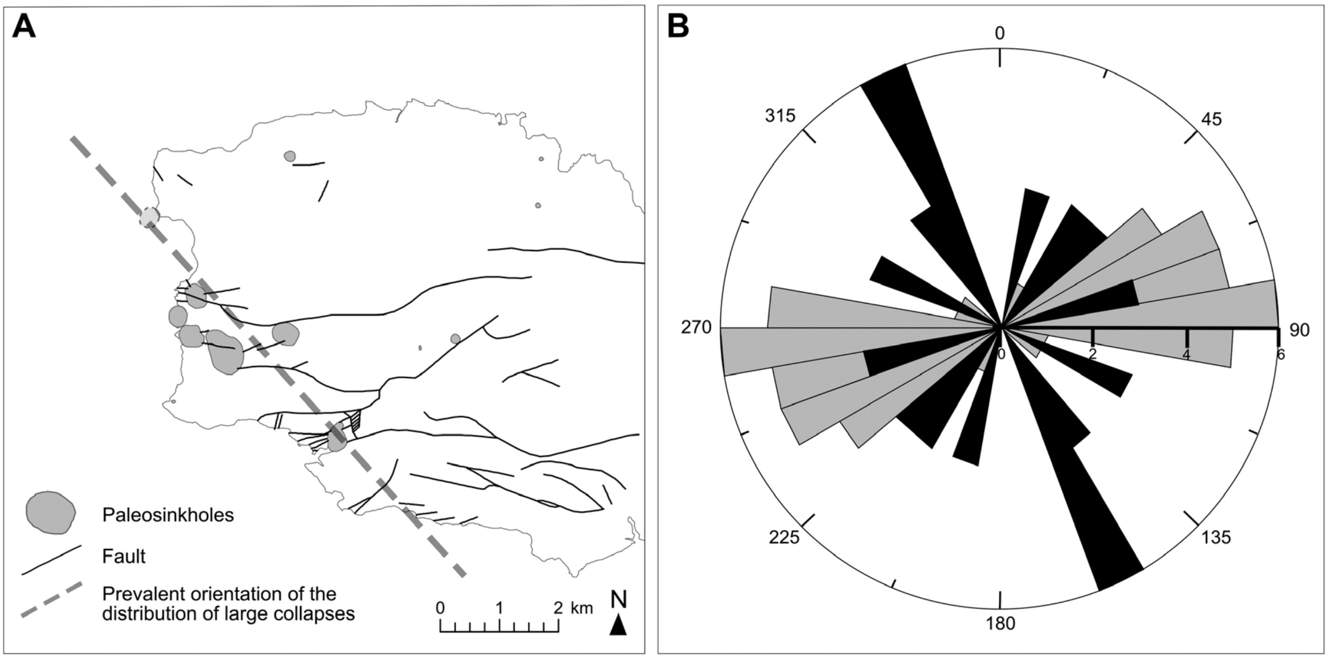

Fig. 2. (**a**) Sketch of the western sector of Gozo showing the NW–SE prevalent distribution of the palaeosinkholes. (**b**) Rose diagram representing azimuth of the lines between the centroid of each palaeosinkhole and that of the nearest one (black) and the strike of the faults mapped in the western sector of Gozo (grey).

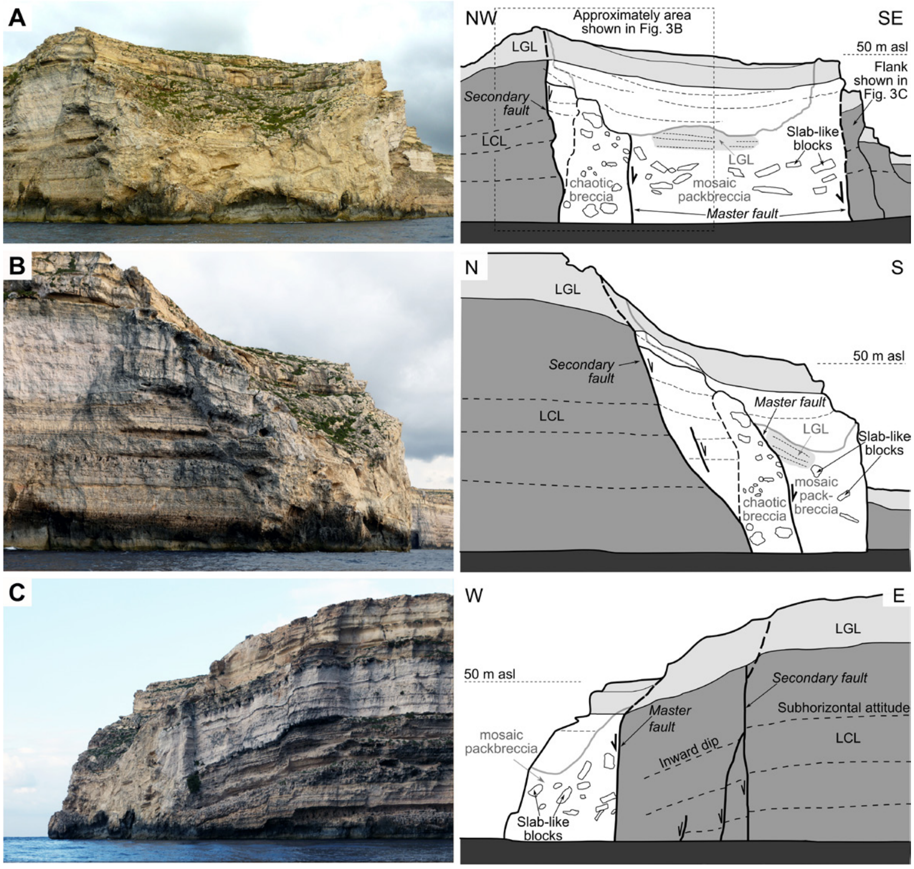

Fig. 3. The Il-Maxell palaeosinkhole. (**a**) Main NW–SE-oriented exposure, with sketch, showing the western edge of the collapse structure controlled by arcuate master and secondary faults. (**b**) Northern side of the exposure and sketch. (**c**) Southern exposure with sketch. The Il-Maxell structure is the only palaeosinkhole of Gozo in which it is possible to observe the deformation style in the sediments underlying the depression fill, a mosaic packbreccia (Warren 2006), largely consisting of metre-sized slab-like blocks of fragmented and dislocated tabular beds.

These oblique faults might still be active and are very probably related to the formation of the ENE–WSW North Gozo Graben, which started in the Late Pliocene and shows evidence of very recent activity (Gardiner *et al.* 1995).

Regarding the spatial distribution, the five palaeosinkholes in the western coastal sector of the island of Gozo are tightly clustered (Fig. 1b). The Xlendi and Tal Harrax structures, which have elongated geometries and sharp changes in width, may correspond to the coalescence of adjoining palaeosinkholes (Fig. 1b). Hereabouts, the development of the collapse structures seems to have been controlled by NW–SE-trending faults. The Dwejra North, Dwejra Bay and Tal Harrax structures form a clear tightly

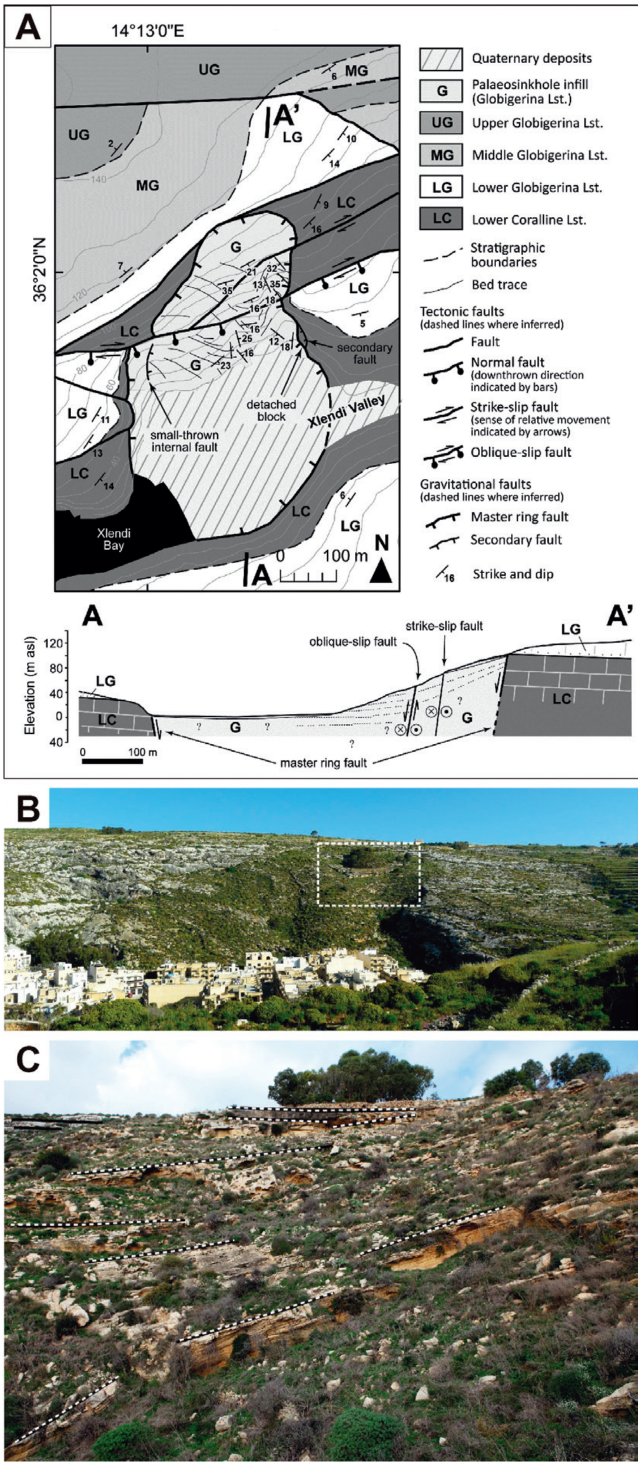

Fig. 4. (**a**) Detailed geological map and cross-section of the Xlendi palaeosinkhole, offset by oblique dextral-normal tectonic faults. Several small throw radially disposed dip-slip faults in the structure affect the sinkhole infill. (**b**) General view of the Xlendi collapse from the south. (**c**) Cumulative wedge-out and progressive upward dip attenuation in the Globigerina Limestone strata of the palaeosinkhole fill (NE margin).

packed NW–SE alignment, and the major axis of the Tal Harrax elongated structure is oriented in the same direction (Fig. 2a). The rose diagram in Figure 2b shows the azimuth of the lines drawn between the centroid of each palaeosinkhole and its nearest neighbour, plus the strikes of the faults mapped in the area. The lack of coincidence between the prevalent NW–SE orientation inferred for the sinkholes and the strike of the tectonic faults suggests that (1) the development of the collapse structures may have been controlled by NW–SE-trending buried faults or joints with no cartographic expression, and (2) the oblique-slip faults that offset the whole Tertiary stratigraphic succession and the collapse structures may have formed after the development of the palaeosinkholes.

Regarding the internal structure of the collapses, they are essentially downdropped blocks bounded by steeply dipping annular faults. Some structures seem to be controlled by a single master ring fault (Il-Maxell, Xlendi, Qwara, Tal Harrax, Ghajn Abdul; Figs 3, 4a, 5a, b, 6a, c and 7) whereas others include nested failure planes with concentric (Qawra, Tal Harrax, Dwejra Bay; Figs 5a, c, 6a and 8) or exocentric arrangement (Dwejra North Bay; Fig. 8). Small throw secondary faults (e.g. Il-Maxell, Xlendi and Qawra; Figs 3, 4a and 5a) and inward dips (e.g. Tal Harrax; Fig. 6b) are common in the periphery of the collapses.

The palaeosinkholes' infill shows the following characteristics (Pedley 1974; Pedley & Bennet 1985): (1) some Miocene units are thicker in the collapsed blocks than in the surrounding areas (Xlendi, Ghajn Abdul), and may also wedge out towards the rim of the palaeosinkholes (Il-Maxell, Xlendi, Tal Harrax; Fig. 4c); (2) the strata in the collapsed plug typically display a basin structure with centripetal dips (e.g. Xlendi, Tal Harrax, Ghajn Abdul; Figs 4a, 6a, b and 7a); (3) the infill shows local changes in the depositional processes and facies; this is clear in the cases of Xlendi (Fig. 4b and c) and Ghajn Abdul (Figs 7c and 9a); (4) the sediments of the palaeosinkhole fills abutting the marginal collapse faults may include allochthonous blocks fallen from an adjacent submarine sinkhole scarp, which may be accompanied by soft sediment deformation (Qawra, Tal Harrax, Ghajn Abdul; Figs 5d, 6d and 9b).

The Dwejra area in western Gozo has a dramatic coastal landscape related to a cluster of four of the studied palaeosinkholes and represents an area of special interest (Figs 1b and 10; Coratza *et al.* 2012). These collapse structures are spatially associated with a peculiar monoclinal structure, described earlier by Pedley & Bennet (1985). A structure-contour map of the top of the Lower Coralline Limestone has been constructed to characterize the fold (Fig. 10a). This is a west-facing semicircular monocline with centripetal dips and a maximum radius of about 900 m, which resembles half of a structural basin. The lack of offshore data precludes elucidating whether the structure corresponds to a complete structural basin, or to a tightly curved down-to-the-west monocline. The structural relief of the monocline, as indicated by the top of the Lower Coralline Limestone contour map, is around 60 m. The measured dips on the Tertiary strata are lower than 10° (or horizontal) in the upper and lower limbs, and exceed 15° in the dipping limb. Dwejra North palaeosinkhole, currently submerged by the sea, is located in the centre of the arcuate monocline, whereas Qawra, Tal-Harrax and Dwejra Bay palaeosinkholes partially overlap the dipping limb and/or the crest of the monocline (Fig. 10).

Discussion

The island of Gozo shows unique examples of large collapse structures with dramatic geomorphological expression related to differential erosion controlled by the contrasting erodibility between the downdropped sediments and the surrounding bedrock (Soldati *et al.* 2013). These gravitational structures have been interpreted as dissolution-induced submarine palaeosinkholes that were active in the Miocene during the deposition of stratigraphic units overlying the Lower Coralline Limestone. Two hypotheses have been proposed to explain their genesis: (1) collapse of large caves developed within the Lower Coralline Limestone (Pedley 1974); (2) deep-seated dissolution of halite-bearing evaporites and collapse of the overlying caprock sediments (Illies 1980).

According to the interpretation of Pedley (1974), the palaeosinkholes result from the collapse of large caverns developed within the Lower Coralline Limestone. Pedley, inspired by the

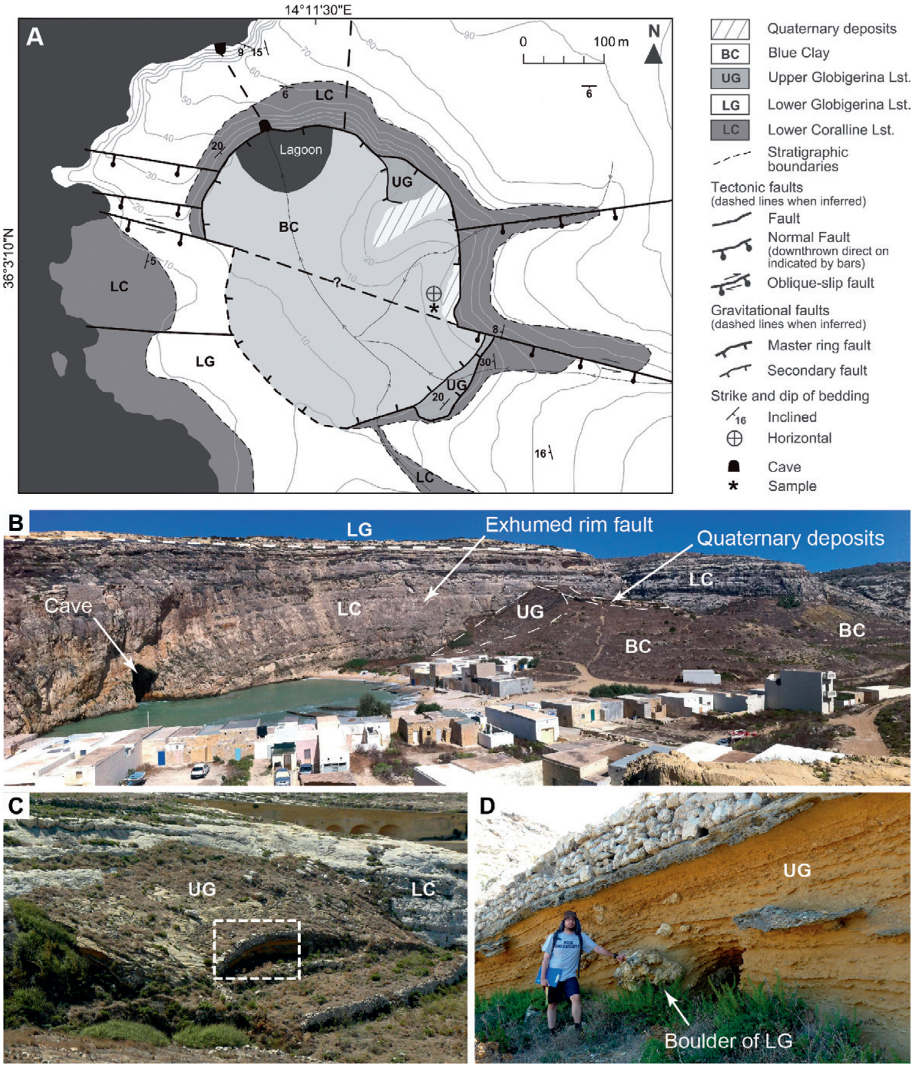

Fig. 5. (**a**) Detailed geological map of the Qawra palaeosinkhole. Most of the collapse depression is underlain by the Blue Clay, largely masked by vegetation, but where exposed these sediments show an undisturbed dominant subhorizontal structure. Two samples were collected from this stratigraphic unit for planktonic foraminifera assemblage biostratigraphy (the asterisk indicates the location of samples). The lower sample contained *Paragloborotalia siakensis, Dentoglobigerina altispira* and *Globigerinoides* spp. The upper one had more and better developed *P. siakensis* and scarce *Paragloborotalia partimlabiata*. According to Abels *et al.* (2005), the first occurrence of *P. partimlabiata* is found in the upper part of the Blue Clay, suggesting that the exposed sediments correspond to the middle and upper sections of the Blue Clay. (**b**) View of the NE sector of the erosional depression excavated within the palaeosinkhole. The steep scarp on Lower Coralline Limestone corresponds to the exhumed rim fault of the collapse structure. The vegetated slopes at the foot of the scarp are underlain by softer Blue Clay and Upper Globigerina Limestone. The lagoon is connected to the sea through a fault-controlled cave. (**c**) SE margin of the collapse, where Upper Globigerina Limestone (vegetated slope) is juxtaposed with Lower Coralline Limestone (bare rock exposure). (**d**) Boulder of reworked Lower Globigerina Limestone incorporated within the Upper Globigerina Limestone deposited in the palaeosinkhole. The boulder is interpreted as a block fallen from the scarped margin of the submarine sinkhole in Miocene time. LC, Lower Coralline Limestone; LG, Lower Globigerina Limestone; UG, Upper Globigerina Limestone; BC, Blue Clay.

'blue holes' of the Caribbean region, suggested that the cave systems formed during a probable emergence phase in the Eocene or Oligocene period. Sea-level falls of *c*. 50–60 m have been reported in the global sea-level curves at the Eocene–Oligocene boundary and in the Middle Oligocene (Miller *et al.* 2011). Relative sea-level falls of 10–20 m have been reported over the Malta Platform in the early Chattian period by Gatt & Gluyas (2012). However, none appear to have been sufficient to place western Gozo more than a few metres above sea level.

Illies (1980) succinctly presented his evaporite dissolution interpretation without providing many supporting data. Surprisingly, he used the oblique-slip faults that offset the palaeosinkholes as diagnostic indicators of deep-seated salt dissolution and caprock collapse. This highly questionable concept was based on the interpretation by Belderson *et al.* (1978) of similar features recognized in the sea floor of the eastern Mediterranean. According to those researchers, in their study area strike-slip faulting may have allowed seawater access to an underlying salt layer, triggering its dissolution. However, in our case study the oblique-slip faults are superimposed on the palaeocollapses, and consequently postdate them.

Below we discuss the origin of the Gozitan palaeosinkholes considering the available geological data and analysing the similarities and differences compared with other large sinkholes and collapse structures related to evaporite and carbonate dissolution documented worldwide, both onshore and offshore.

Subsidence kinematics and duration

Overall, the available data indicate that the collapse process in the study area operated over a very long period of time in the late Cenozoic. The subsidence kinematics was probably dominated by progressive deformation, rather than by major episodes of gravitational faulting. The study of the palaeosinkholes infill provides multiple evidence of synsedimentary subsidence in the sea floor (Pedley 1974; Pedley & Bennet 1985), as follows.

(1) Cumulative wedge-out arrangements occur in the palaeosinkhole fill (Fig. 4c).

(2) The boulders entombed in the fill indicate that there were periods during which subsidence was not counterbalanced by aggradation (Figs 5d, 6d and 9b).

(3) The depressions created by collapse subsidence in the sea floor controlled changes in the depositional processes and facies. Moreover, in some palaeosinkholes synsedimentary subsidence has been active over several periods. For instance, in Tal Harrax the available data indicate that progressive subsidence has been active during deposition of the Globigerina Limestone and the Blue Clay, probably spanning around 10 Ma in the Miocene

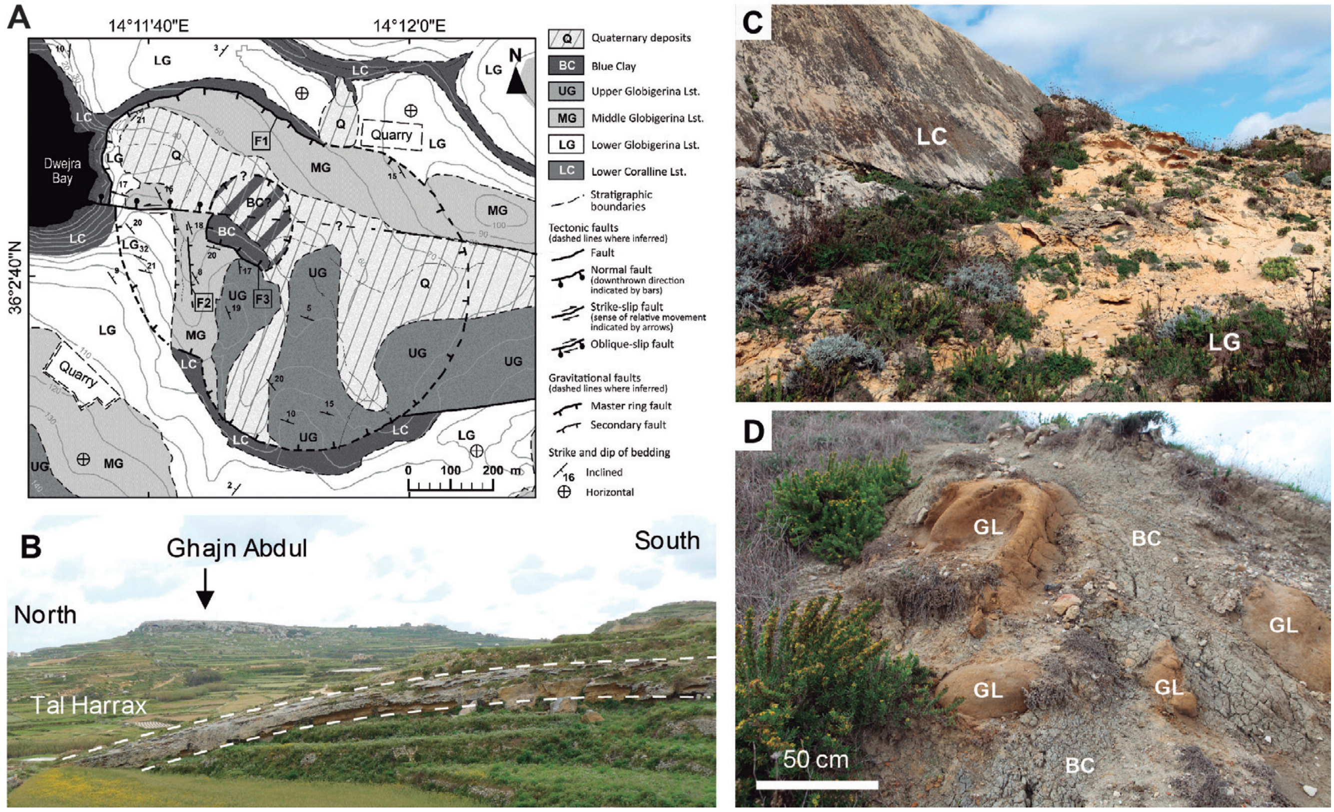

Fig. 6. (**a**) Detailed geological map of the Tal Harrax palaeosinkhole. (**b**) Sagging strata of Upper Globigerina Limestone at the southernmost sector of Tal Harrax depression. (**c**) Tal Harrax rim fault outcrop. LC, Lower Coralline Limestone; LG, Lower Globigerina Limestone. (**d**) Boulders of Globigerina Limestone (GL) entombed within Blue Clay (BC) deposits at the centre of Tal Harrax structure. This Blue Clay outcrop contains a high detrital fraction, including abundant glauconite clasts, suggesting that it may correspond to the upper part of the formation, close to the contact with the Greensand Formation (Giannelli & Salvatorini 1975). This interpretation is supported by the planktonic foraminifera assemblage in two samples collected for this investigation (*P. siakensis, P. partimlabiata* and *Globorotalia menardii)*.

(Fig. 6). Stratigraphic evidence in Ghajn Abdul suggests that subsidence may have been active during deposition of the Upper Coralline Limestone (Fig. 7). Two collapse structures also record that significant subsidence occurred after the sedimentation of the Upper Coralline Limestone (Wardija Point, Wied il-Mielah; Fig. 11). Moreover, the nested enclosed depression 160 m across and 4 m deep identified in the submerged floor of Dwejra North Bay suggests that some collapses have been active in recent times (Fig. 8).

Therefore, the analysed subsidence phenomenon can be explained by progressive interstratal dissolution of soluble rocks at depth over a very long time period, and the concomitant gradual collapse of the overlying formations. These features related to the subsidence kinematics and duration seem to be more compatible with interstratal dissolution of evaporites.

The stratigraphic relationships of both the Crater Lake structure and the Saskatoon low, Saskatchewan, Canada, indicate that deep-seated salt dissolution and synsedimentary subsidence have been active over several periods from the Late Cretaceous to the late Pleistocene (Christiansen 1971; Christiansen & Sauer 2001). In the Delaware Basin, New Mexico and Texas, USA, dissolution of Permian evaporites has generated depositional basins filled with Neogene continental sediments that may reach 50 m in thickness (Hill 1996, and references therein). Synsedimentary subsidence related to interstratal karstification of salt-bearing evaporites has been also documented in a number of fluvial valleys, where Quaternary alluvium shows substantial thickenings in dissolution basins (Guerrero *et al.* 2013, and references therein; Gutiérrez & Cooper 2013). In contrast, the sedimentary fill in large sinkholes related to the collapse of limestone caves commonly shows parallel-layered strata indicating that subsidence has not been active during deposition. A good example of this is the Holocene fill of the Blue Hole of Light House Reef, Belize, where there is no evidence of growth strata (Gischler *et al.* 2013). This steep-sided submarine sinkhole of 120 m depth and 320 m width was formed in the late Pleistocene by the collapse of a water table cave (White 1988). Features indicative of synsedimentary subsidence have also been documented in limestone karst sinkholes, although with notable differences from those observed in the Gozitan collapses. For instance, in lakes of north–central Florida related to the coalescence of sinkholes, high-resolution seismic data reveal geometrical relationships in the deposits indicative of synsedimentary subsidence, but these are spatially and temporally restricted, and related mainly to suffusion processes and dissolution at the rockhead (Kindinger *et al.* 1999).

Dimensions and deformation style

A striking feature of the studied palaeosinkholes is their gigantic dimensions. In the Maltese Archipelago, cave systems have been developed in the Lower Coralline Limestone during Quaternary sea-level lowstands, and locally roof breakdown has resulted in the development of collapse sinkholes (Pedley 1974; Pedley *et al.* 2002). There are several significant onshore and offshore examples. Il-Maqluba sinkhole in southern Malta is an elliptical depression 100 m long with vertical cliffs 30 m high. There are also well-known submarine caves (e.g. Blue Dome, northern Gozo) and sinkholes (e.g. Blue Hole, Dwejra area, western Gozo, Fig. 10a), the latter up to 25 m

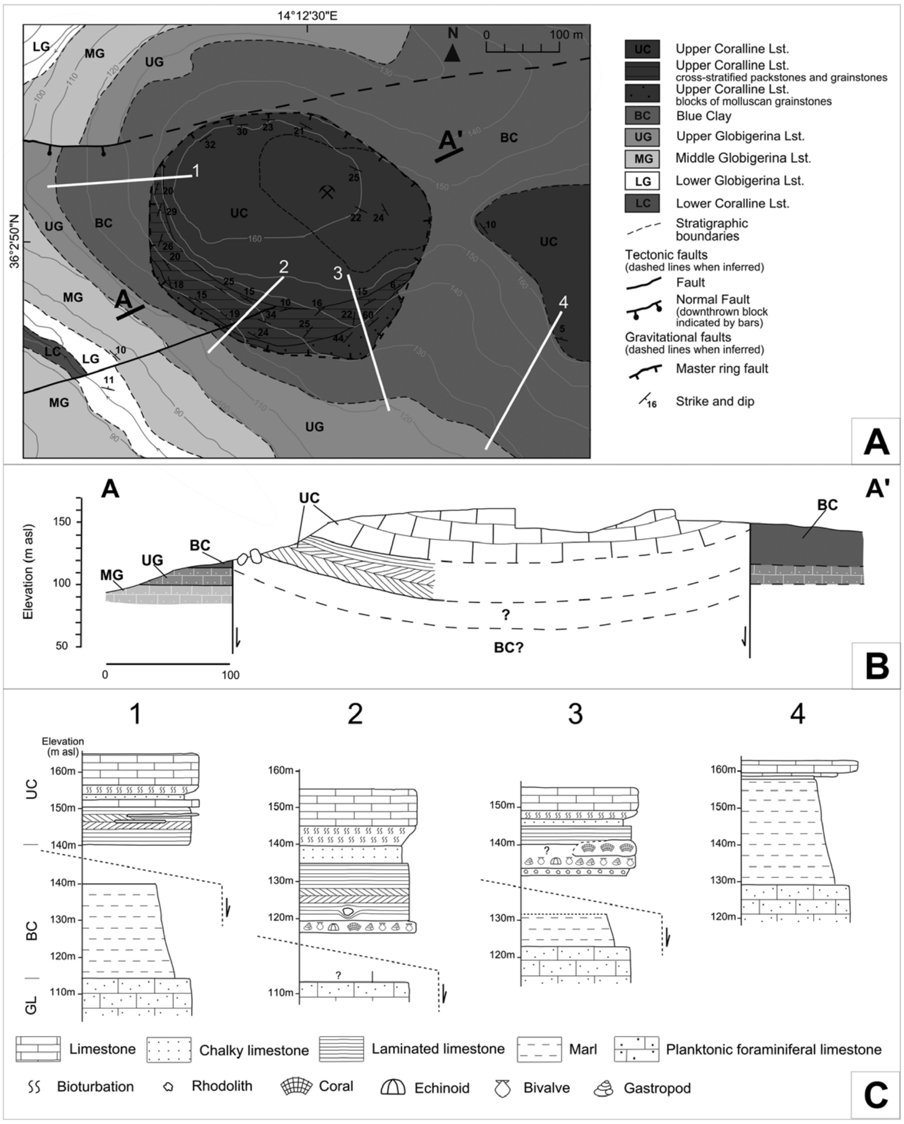

Fig. 7. Detailed geological map of the Ghajn Abdul palaeosinkhole (**a**) and cross-section (**b**). The numbers in the geological map indicate the stratigraphic sections shown in (**c**). (**c**) Stratigraphic sections recorded in Ghajn Abdul palaeosinkhole (1, 2 and 3) and in the adjacent mesa.

across and 15 m deep (Lemon 2012). However, the size of these collapses, as well as their subsidence mechanism and kinematics, are very different from those of the Miocene palaeosinkholes (Tonelli *et al.* 2012). These data indicate that large cavities exist within the Lower Coralline Limestone, but they are most probably much younger than the Miocene palaeosinkholes and not large enough to form tightly clustered collapses several hundred metres across.

The largest documented caverns and collapse sinkholes associated with carbonate rocks occur in inland mature karsts developed in massive limestones that have a high mechanical strength, usually in humid tropical regions. The largest known cavern is Sarawak Chamber in Gunung Mulu National Park, Malaysia. This underground void is 700 m long, 400 m wide and its vault-shaped ceiling reaches around 100 m in height (Waltham 2004, 2006). The largest collapse sinkholes are the Tiankengs in China. These are giant sinkholes related to the collapse of large chambers, commonly associated with substantial cave rivers (Waltham *et al.* 2005; Zhu & Waltham 2006). Xiaozhar Tiankeng, also known as the Heavenly Pit, is 628 m long and 662 m deep. Deep collapse dolines have been also documented in the Dinaric karst, such as Crveno Jezero sinkhole, Croatia. This is a vertical-walled collapse around 500 m wide and more than 530 m deep, half submerged under a lake (Garašić 2000). However, it is not clear whether this collapse structure is rooted in carbonate or evaporite rocks.

Although the size of the palaeosinkholes in Gozo is comparable with those of the aforementioned carbonate karst landforms from China, there are significant differences regarding the subsidence mechanism. The roof of large caverns developed in limestone typically propagates upward through successive collapses controlled by arched failure planes. Ground subsidence does not occur until the stoping process reaches the surface, leading to the catastrophic formation of a collapse sinkhole. In contrast, as the stratigraphic record reveals, subsidence has affected the sea floor over millions of years, indicating long-sustained deep-seated dissolution and sinkhole rejuvenation. In the analysed palaeosinkholes this subsidence has been accommodated by the progressive foundering of cylindrical plugs with limited internal deformation. This is clearly observable in the case of the Qawra structure (Fig. 5). The downdropped blocks bounded by steeply dipping annular faults of the palaeosinkholes are similar to those documented in volcanic calderas related to the slow decline of the supporting magma. According to Roche *et al.* (2001), the foundering of this type of piston-like integral blocks develops when the roof has an aspect ratio (roof thickness/roof width) within a specific range, which depends on the mechanical properties of the rocks. This deformation style of the palaeosinkholes of Gozo is very similar to the subsidence mechanism in other collapse structures related to interstratal dissolution of salt-bearing evaporites described in the literature. The Crater Lake depression, Saskatchewan, Canada, is a circular topographic basin underlain by a downthrown cyclindrical block with two concentric fault zones 100 and 200 m in diameter. This collapse, with a vertical throw of 73 m, is related to interstratal

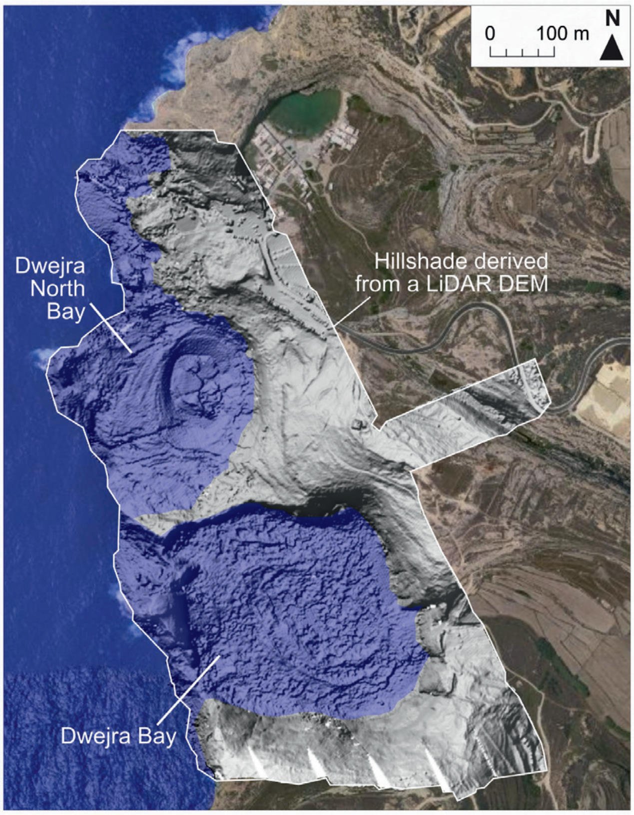

Fig. 8. Digital elevation model generated from LiDAR data, showing the topography of the sea floor at Dwejra North Bay and Dwejra Bay. The steep-sided enclosed depression in the NE sector of the bay controlled by the collapse structure should be noted. The bottom of the closed depression has a marginal trough and a protruding central sector with blocky appearance.

dissolution of the halite-bearing Middle Devonian Prairie Evaporite Formation, located at a depth of 914 m (Christiansen 1971; Gendzwill & Hajnal 1971). The 45 km long structural basin of the Saskatoon Low, Saskatchewan, Canada, is controlled by subvertical faults generated by interstratal dissolution of Devonian salts, whose original thickness coincides with the maximum throw of the structure (Christiansen 1967). This basin includes nested collapse structures bounded by ring faults several kilometres in diameter (Christiansen & Sauer 2001). In the Canyonlands section of the Colorado Plateau, USA, interstratal dissolution of evaporites in salt-cored anticlines has produced collapse structures controlled by vertical failure planes with circular and concentric forms. The downthrown blocks reach more than 500 m in diameter, are rooted in evaporites at a depth of more than 600 m, and show vertical displacements up to 300 m (Weir *et al.* 1961; Cater 1970; Sugiura & Kitcho 1981; Gutiérrez 2004). In the Calatayud Neogene Graben, Iberian Chain, NE Spain, interstratal karstification of halite- and glauberite-bearing evaporites has generated collapses several kilometres across with a vertical displacement of more than 200 m. Here the marginal faults of the collapse structures have an irregular cartographic trace (Gutiérrez 1996, 2014).

Although the structures of the palaeosinkholes of Gozo have characteristics of deep-seated collapses induced by interstratal evaporite dissolution, similar structures identified using 3D seismic data have been attributed to the dissolution of carbonate rocks. Brown (1999) recognized karst pits 200–500 m in diameter in deep burial Miocene carbonate rocks of the Gippsland basin, southeastern Australia. Castillo & Mann (2006) identified subcircular features up to 600 m wide and about 100 m deep in the Lower Cretaceous carbonates of the Cogollo group in the southern Maracaibo Basin, Venezuela. These features were interpreted as sinkholes formed subaerially by tropical weathering during a well-known eustatic drop in the sea level that occurred during the Aptian period in the Maracaibo region. In the northern Fort Worth basin, Texas, McDonnell *et al.* (2007) identified subcircular collapse and sagging structures 500–2000 m in diameter that extend vertically for 760–1060 m. They explained these subsidence features as the coalescence of linked palaeocaves in a limestone formation (Ellenburger Group) with incremental collapse of the overlying strata. In the northern South China Sea, 221 dissolution-collapse pipe structures 100–710 m wide and 134–1010 m deep were identified by Sun *et al.* (2013). In the Gulf of Lions, SW France, Lofi *et al.* (2012) used seismic profiles to image a subcircular collapse structure 2 km wide and 800 m deep with inward dipping concentric faults and an inner sagging structure. The researchers attribute the genesis of the subsidence structures described in China and France to the collapse of limestone caves, although they did not have direct data on the soluble rock units at depth.

Spatial association with an arcuate monocline

The Dwejra palaeosinkhole cluster is spatially associated with a peculiar west-facing semicircular monocline suggesting a genetic link. The monocline has a radius of around 900 m and a structural relief of *c.* 60 m. Monoclines related to the down-dip migration of dissolution fronts in evaporites and the consequent subsidence of the overlying strata (drape gravitational folding) have been documented in numerous regions: Saskatchewan, Canada (Hopkins 1987; Anderson *et al.* 1988), NE England (Cooper 2002), SW and central sectors of the USA (De Mille *et al.* 1964; Walters 1978; Anderson *et al.* 1994; Neal & Colpitts 1997; Gutiérrez *et al.* 2014), central Saudi Arabia (Powers *et al.* 1966; Memesh *et al.* 2008), Thailand (Supajanya & Friederich 1992) and NE Spain (Gutiérrez *et al.* 2012). Some of these dissolution-induced monoclines are accompanied by large caprock collapse sinkholes. In the Interior Homocline of central Saudi Arabia, dissolution of Late Jurassic anhydrite–gypsum units has generated a sinuous monocline more than 500 km long, locally affected by large caprock collapse sinkholes including Dahl Hit (Memesh *et al.* 2008; Gutiérrez & Cooper 2013). The sinkholes of Bottomless Lakes State Park, New Mexico, USA, are a sinuous chain of collapse sinkholes that traverse a dissolution-induced monoclinal scarp on the eastern margin of the Pecos River valley (Land 2003). The Holbrook Anticline in northern Arizona is a monocline generated by interstratal dissolution of halite- and sylvite-bearing Permian evaporites at more than 200 m depth. A number of active subsidence depressions 2–3 km across with nested sinkholes (e.g. McCauley Sinks, Richard Lake) have been identified linked to this gravitational drape fold (Conway & Cook 2013; Neal *et al.* 2013).

Soluble rocks in the subsurface

The available borehole data indicate the presence of very thick carbonate units with dissolution-related cavern formation throughout the Tertiary and Mesozoic succession underlying the Globigerina Limestone (Pedley 1974). In contrast, the reported evaporitic units are very deep or have a limited thickness. The Late Triassic anhydrite beds recorded in Madonna Taz-Zejt 1ST1 borehole have a cumulative thickness of around 230 m, but occur below 4.5 km depth (Debono *et al.* 2000). The relative shallow gypsum bed found 100–150 m below the base of the Lower Coralline Limestone in the Malta Platform is just 1 m thick (Gatt & Gluyas 2012). These data challenge the evaporite dissolution hypothesis. Dissolution-induced collapse structures around 1 km deep have been reported by several researchers (e.g. Lu & Cooper 1996; McDonnell *et al.*

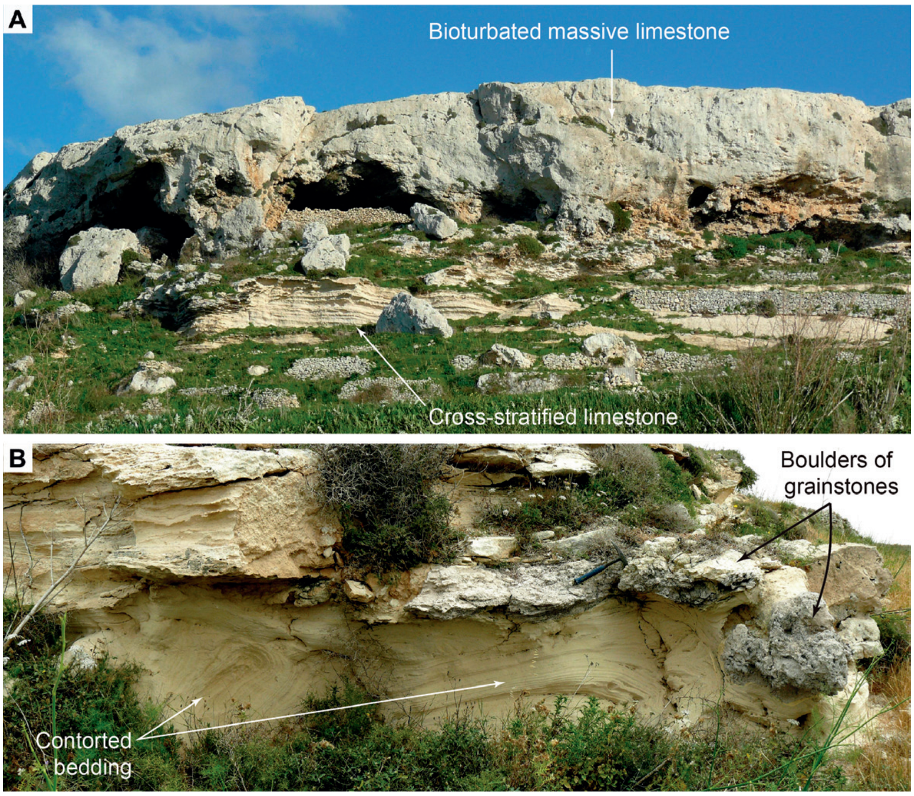

Fig. 9. (**a**) Upper part of Ghajn Abdul mesa capped by Upper Coralline Limestone. The low-angle cross-stratified packstones and grainstones overlain by bioturbated massive limestone at the top should be noted. (**b**) Load casts and contorted bedding in the cross-stratified packstones and grainstones associated with large metre-sized allochthonous boulders of grainstones containing pectinids, echinoderms, oysters and gastropods.

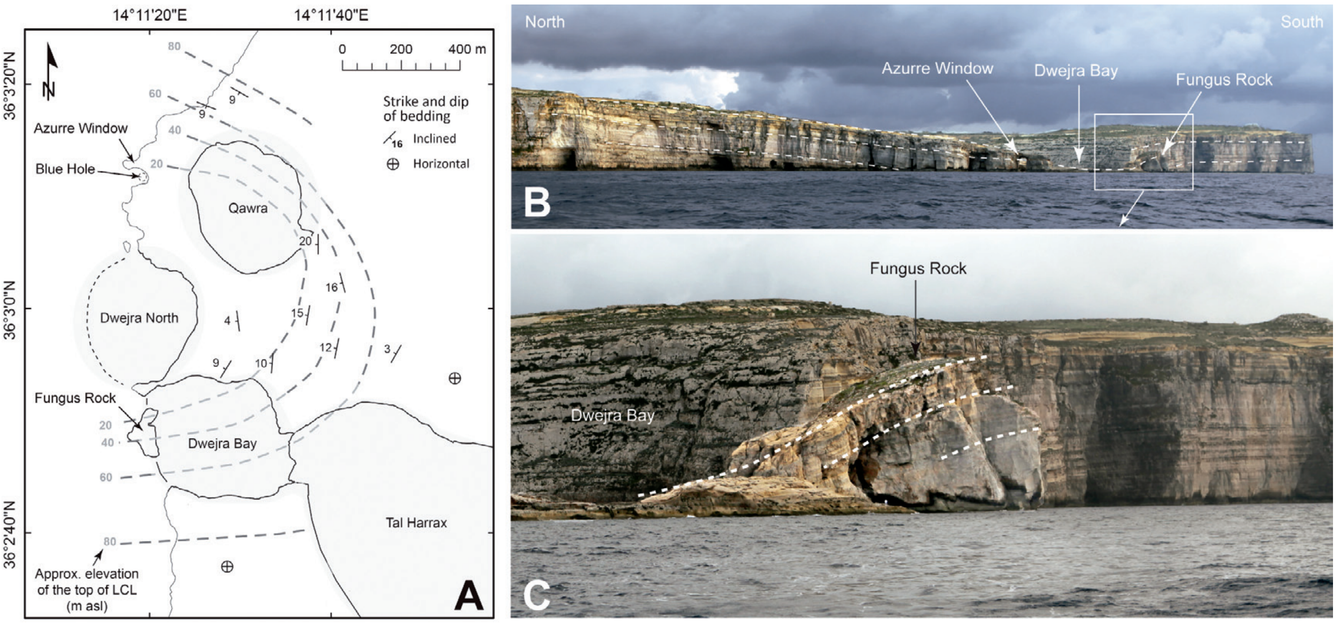

Fig. 10. (**a**) Structure contour map of the top of the Lower Coralline Limestone illustrating the arcuate west-facing monoclinal structure of Dwejra area. (**b**) General view of the west sector of the monocline from the sea. (**c**) Detail of the attitude of the strata at Fungus Rock.

2007; Lofi *et al.* 2012), but to our knowledge, never as deep as 4.5 km. However, there is the possibility that during the development of the palaeosinkholes in the Miocene, there were halite-bearing evaporites that have been largely removed by dissolution. As Warren (2006) indicated, a large proportion of the evaporitic formations deposited in the Earth's history have been largely removed from the rock record by subsurface dissolution, and in many cases the only evidence of their previous existence corresponds to frequently overlooked pointers of karstification such as insoluble residues or breccias. The size of the palaeosinkholes in Gozo decreases towards the NE. This spatial trend might be related to some kind of stratigraphic control, such as the wedging out towards the NE of the soluble rock responsible for the collapse structures.

Mechanism of karstification

Large collapse sinkholes are usually formed in geological settings where buried evaporites are present (e.g. Paradox Valley and Delaware Basin, USA) or where large-scale carbonate dissolution has occurred (e.g. China and Dinaric karst). Two main modes of large-scale carbonate dissolution have been documented in different karst settings: (1) karstification in a subaerial or shallow-burial environment by meteoric waters in humid regions; (2) deep-burial

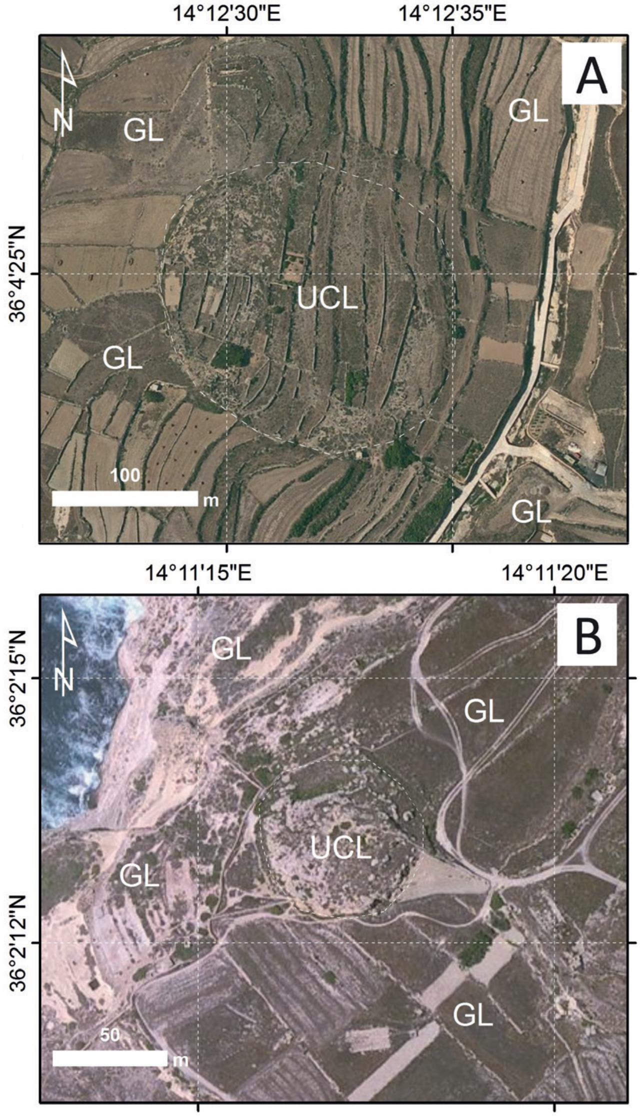

Fig. 11. Aerial orthoimages of Wied il-Mielah (**a**) and Wardija Point (**b**) palaeosinkholes. The cartographic relationships observed in these structures indicate that the collapses were active after the deposition of the Upper Coralline Limestone in Pliocene and probably Quaternary times. UCL, Upper Coralline Limestone; GL, Globigerina Limestone.

carbonate dissolution owing to circulation of deep aggressive fluids. The first model cannot be invoked for the generation of the Maltese palaeocollapses because of their deep-seated origin and evolution in a submerged environment. Several palaeosinkholes show syndepositional subsidence during the sedimentation of the Globigerina Limestone Formation. This formation records a long period spanning *c*. 10 Ma (Aquitanian–Langhian) of sedimentation in the sea floor below the action of waves, interrupted by shallowing phases represented by hardgrounds and phosphorite conglomerate beds also formed below sea level (Pedley *et al.* 2002; Föllmi *et al.* 2007).

Deep-burial carbonate dissolution can result from the circulation of corrosive fluids. The aggressiveness of these fluids on carbonate rocks may be enhanced by CO_2 (normally geothermal fluids) or H_2S (basinal fluids, connate waters) enrichments, which are characteristics of active volcanic regions or areas adjacent to oil or gas fields (Ford & Williams 2007).

Sinkholes and collapse structures related to CO_2-enriched geothermal fluids have been documented in numerous regions, including dissolution-collapse pipes in the South China Sea related to a magma intrusion (Sun *et al.* 2013), sinkholes of the Sistema Zacatón, Mexico (Gary & Sharp 2006), the Obrucks of central Anatolia, Turkey (Bayari *et al.* 2009), and collapse sinkholes of the San Vittorino Plain and Pontina Plain, Italy (Salvati & Sasowsky 2002). However, volcanic activity in the Maltese archipelago was restricted to the Jurassic (Patacca *et al.* 1979) and consequently it cannot be responsible for the Gozitan palaeocollapses.

Large-scale deep-burial carbonate dissolution may also be caused by acid pore waters resulting from hydrocarbon degradation. Large caves have been formed as a result of this mechanism, including the famous Carlsbad Caverns and Lechuguilla Cave, New Mexico. However, this alternative can also be ruled out because, among other constraints, this process creates large caves at and around the water table where the H_2S rising from depth mixes with O_2-rich meteoric waters (Ford & Williams 2007). Therefore, it is not consistent with the submerged environment of formation of the Gozitan palaeosinkholes.

The mixing of two fluids saturated in calcite may change the saturation state of the new solution. According to Corbella & Ayora (2003) the mixing of two fluids in deep aquifers is much more important for carbonate dissolution than the changes induced by the oxidation of H_2S. According to their calculations, this is due purely to the mixing effect. No dissolution at the scale of karst conduits would be expected by mixing two fluids with temperatures that differ less than 10 °C. Although these mechanisms have been invoked to enhance porosity in deep carbonate reservoirs, the modality and extent of karst features possibly formed by burial carbonate dissolution are not well known and have been recently questioned by Ehrenberg *et al.* (2012).

Conversely, evaporite dissolution in sub-sea burial environments is still poorly understood, but it has been documented in the eastern Mediterranean basin (Ross & Uchupi 1973; Kastens & Spiess 1984; Bertoni & Cartwright 2005) and in the North Sea (Lohmann 1972; Jenyon 1983). Thus, the mechanism of karstification associated with the Maltese palaeosinkholes may be related to dissolution and removal of evaporites by subsea groundwaters. However, the palaeohydrogeological model responsible for the karstification of evaporites is difficult to explain owing to the shortage of data. A model involving groundwater discharge into the sea cannot be invoked because the study area was an isolated carbonate platform when the Gozitan palaeosinkholes started to form (Gatt & Gluyas 2012). A possible conceptual model adapted to this situation is a subjacent dissolution related to focused vertical hydrothermal flow favoured by seismic activity (see Bertoni & Cartwright 2005, for a detailed explanation). According to this mechanism, the dissolution and subsidence that led to the development of the palaeosinkholes may be correlated to tectonically active periods, as reported by Gardiner *et al.* (1995), and not to sea-level changes. This would explain why dissolution-induced subsidence is recorded by the Globigerina Limestone. Deposition of this formation was coeval with periods of activity on the ENE–WSW fault system (Pedley *et al.* 2002). The development of growth faults (Illies 1980) and the opening of Neptunian dykes (cracks formed in the sea floor into which sediment fell; Pedley *et al.* 2002) provide evidence of tectonic deformation affecting the sea floor. The current null, or very low, active subsidence in the palaeosinkholes may be attributed to a tectonic stabilization of the region and/or to the almost total dissolution of the evaporite horizons.

So far, the data available are too limited to propose a robust hypothesis on the origin of the analysed palaeosinkholes. However, the data integrated in this study, together with the discussed points, provide a basis for future studies on the gigantic Gozitan palaeosinkholes and on collapse structures in other regions worldwide.

Conclusion

The detailed analysis of the well-exposed palaeosinkholes of Gozo provides novel insights into the geometry, internal structure, kinematics and origin of the collapse structures. The new knowledge frame, together with data from a number of large dissolution-induced collapse structures documented worldwide, suggests that deep-seated evaporite dissolution is the most satisfactory genetic hypothesis. This interpretation is supported by the following lines of evidence.

(1) The progressive foundering of cylindrical blocks with limited internal deformation over periods lasting of the order of 10 Ma indicates gradual removal of large volumes of evaporite rocks and the concomitant settlement of the overlying strata, rather than the development of large caverns and their upward propagation by stoping, characteristic of limestone karst.

(2) The dimensions and deformation style of the palaeosinkholes are similar to those of other collapse structures related to interstratal dissolution of salt-bearing evaporites.

(3) The arcuate monocline associated with some of the studied palaeosinkholes is a spatial association that is commonly found in areas underlain by evaporitic formations affected by deep-seated dissolution.

However, no major evaporite beds have been documented so far in the subsurface stratigraphy of the Malta Platform. Future subsurface exploration (e.g. deep boreholes and geophysical surveys), as well as petrological and geochemical analyses of Oligocene–Eocene carbonate units may provide new data on potential markers of dissolved evaporites or deep-burial carbonate dissolution. These studies and the examination of currently inaccessible exploration drillholes (e.g. Madonna Taz-Zejt well) might shed some light on the origin of these enigmatic structures and test the hypothesis presented here.

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