APPENDIX 1. DETAILED DESCRIPTION OF THE MIOCENE COLLAPSE STRUCTURES OF THE ISLAND OF GOZO (MALTA, CENTRAL MEDITERRANEAN SEA)

In the descriptions below, the nine analysed palaeosinkholes have been grouped and ordered on the basis of their current geomorphic expression, relative distribution and the type of outcrop features. Three groups are identified: (1) isolated palaeosinkholes with negative relief, showing insight on the internal structure of the collapses (Il-Maxell and Xlendi); (2) Dwejra palaeosinkhole cluster, where the four largest negative relief morphostructures are concentrated (Qwara, Tal-Harrax, Dwejra North and Dwejra Bay); (3) three palaeosinkholes with inverted positive relief including Wardija Point, Wied il-Mielah and especially Ghajn Abdul mesa, which shows the best outcrops.

Il-Maxell palaeosinkhole

The Il-Maxell collapse structure is exposed in an approximately 50 m high cliffed headland in northwestern Gozo, south of San Dimitri Point. Only the eastern edge of the subsidence structure associated with the bounding arcuate faults has been preserved from coastal erosion (Fig. A1). The irregular coastline exposes gravitational deformation structures on sections with different orientations. The overall structure consists of a downthrown block of Lower Coralline Limestone and a few meters of the overlying Lower Globigerina Limestone. The total vertical displacement on the exposed master rim fault and the associated small-throw secondary faults has been estimated at about 15 m. In the main NW-SE-oriented exposure (Fig. A1.A), the Lower Coralline Limestone within the 60 m wide downthrown block of the master fault has been broken into a mosaic packbreccia (Warren 2006), largely consisting of meter-sized slab-like blocks of fragmented and dislocated tabular beds. The fabrics of the blocks delineate a synformal structure with a general dip towards the centre of the collapse. In contrast, the beds of the Lower Globigerina overlying the brecciated Lower Coralline Limestone are laterally continuous (non-brecciated) and seem to wedge out towards the margin of the collapse. These structural and stratigraphic relationships suggest that: (1) the collapse structure has been active when the Lower Coralline Limestone was already lithified to some degree, as revealed by its brittle rheology (postsedimentary subsidence); and (2) subsidence was probably active during deposition of the lowermost beds of the Lower Globigerina Limestone (synsedimentary subsidence). 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. Nonetheless, it is not known whether brecciation affects the Lower Coralline Limestone within the whole structure, or just in an annular band associated with the master collapse fault.

The margin of the collapse structure on the northern side of the exposure shows a ca. 15 m wide shear zone associated with the master collapse fault, consisting of a chaotic breccia of Lower Coralline Limestone (Fig. A1.B). There is also a well-defined, inward-dipping, small-throw secondary fault, which merges with the shear zone. The strata within the sliver between the secondary and the master faults show no internal deformation and subhorizontal attitude. In the southern exposure, the margin of the collapse structure is controlled by subvertical normal and secondary faults (Fig. A1.C). The strata in the footwall of the outermost secondary fault show a subhorizontal structure, whereas in the hanging wall the beds dip around 20º towards the centre of the collapse. Secondary faults show a maximum throw of a few meters. The master fault juxtaposes a breccia of Lower Coralline Limestone, against laterally continuous tilted beds of the same formation.

Xlendi palaeosinkhole

The Xlendi paleocollapse is an isolated subsidence structure on the southwestern coast of Gozo. It shows a N-S trending elongated shape in plan-view, with its southern sector significantly wider than the northern one (Fig. A2). These geometrical features may be related to the coalescence of two adjoining palaeosinkholes. The margins of the structure are mainly underlain by resistant Lower Coralline Limestone, whereas the foundered sediments preserved in the downthrown block correspond to softer Globigerina Limestone (Figs. A2.A). Along most of the perimeter of the gravitational structure, the rim of the palaeosinkhole is conspicuously expressed in the landscape as nearly vertical arcuate scarps on Lower Coralline Limestone, which essentially correspond to the main collapse fault plane exhumed by differential erosion (Fig. A2.A, B). This marginal scarp is interrupted in the southern sector by an ENE-WSW erosional depression associated with Xlendi Bay and Xlendi Valley. This erosional corridor carved across the collapse structure appears to be controlled by the mapped ENE-WSW trending oblique-slip faults (O il Exploration Directorate 1993), and corresponds to the typical Maltese canyon, locally known as a *wied*.

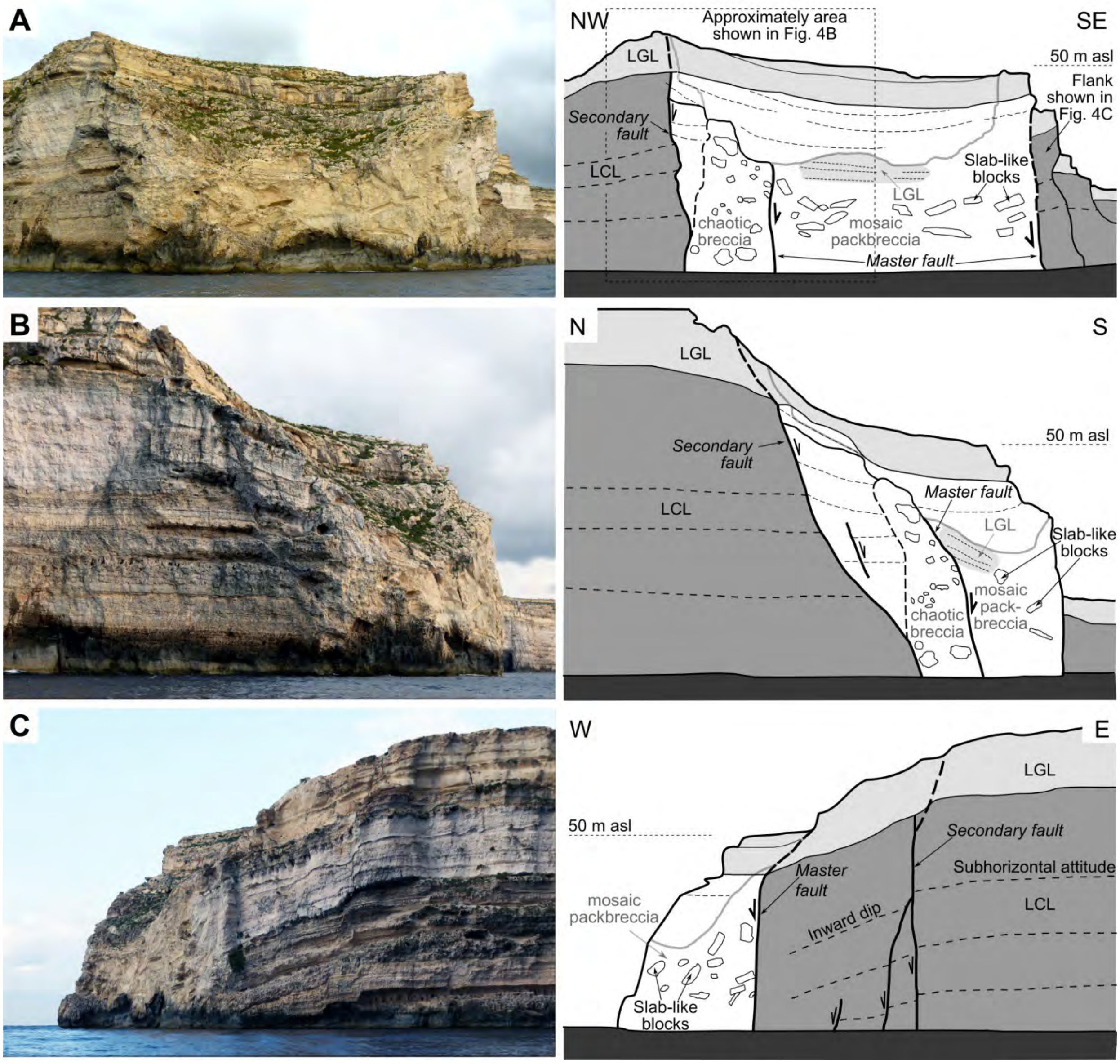

Fig. A1. The Il-Maxell palaeosinkhole. A: Main NW-SE-oriented exposure showing the western edge of the collapse structure controlled by arcuate master and secondary faults. B: Northern side of the exposure and sketch. C: Southern exposure with sketch.

Pedley (1974) and Pedley and Bennet (1985) analysed the paleocollapse infill, focusing on the phosphorite conglomerate beds that includes the Globigerina Limestone. They pointed out several stratigraphic and structural features that provide clues on the development of the palaeosinkhole. (1) The Globigerina Limestone is mainly coarse-grained intraclast wackestone and packstone, which with the interbedded phosphate conglomerate beds, attain a higher thickness in the collapse structure than in the immediate surroundings. Moreover, the Globigerina Limestone beds thicken towards the central sector of the collapse and show a cumulative wedge-out arrangement (progressive upward dip attenuation; Fig. A2.C). Several small throw radially disposed dip-slip faults in the structure affect this infill. These stratigraphic and structural relationships indicate that the palaeosinkholes developed in the sea floor concomitantly with the deposition of the Miocene Globigerina Limestone Beds. The geological map produced for this investigation shows that the Globigerina Limestone beds of the palaeosinkhole fill have significantly higher dips (up to 35º) than the older sorrounding strata. In the northern sector of the collapse infill strike and dip measurements reveal half of an elongated basin structure with dips directed towards the axis and centre of the collapse. In our view, the observed cumulative wedge-outs (Fig. A2.C), and the lack of internal unconformities, plus the colluvial wedges at the margins of the preserved palaeosinkhole fill, suggest that synsedimentary subsidence essentially occurred progressively over a long time span, rather than through major discrete collapse events. (2) The Globigerina Limestone in the paleocollapse infill consists of an anomalous admixture of conglomeratic material with muddy wackestone. The poorly

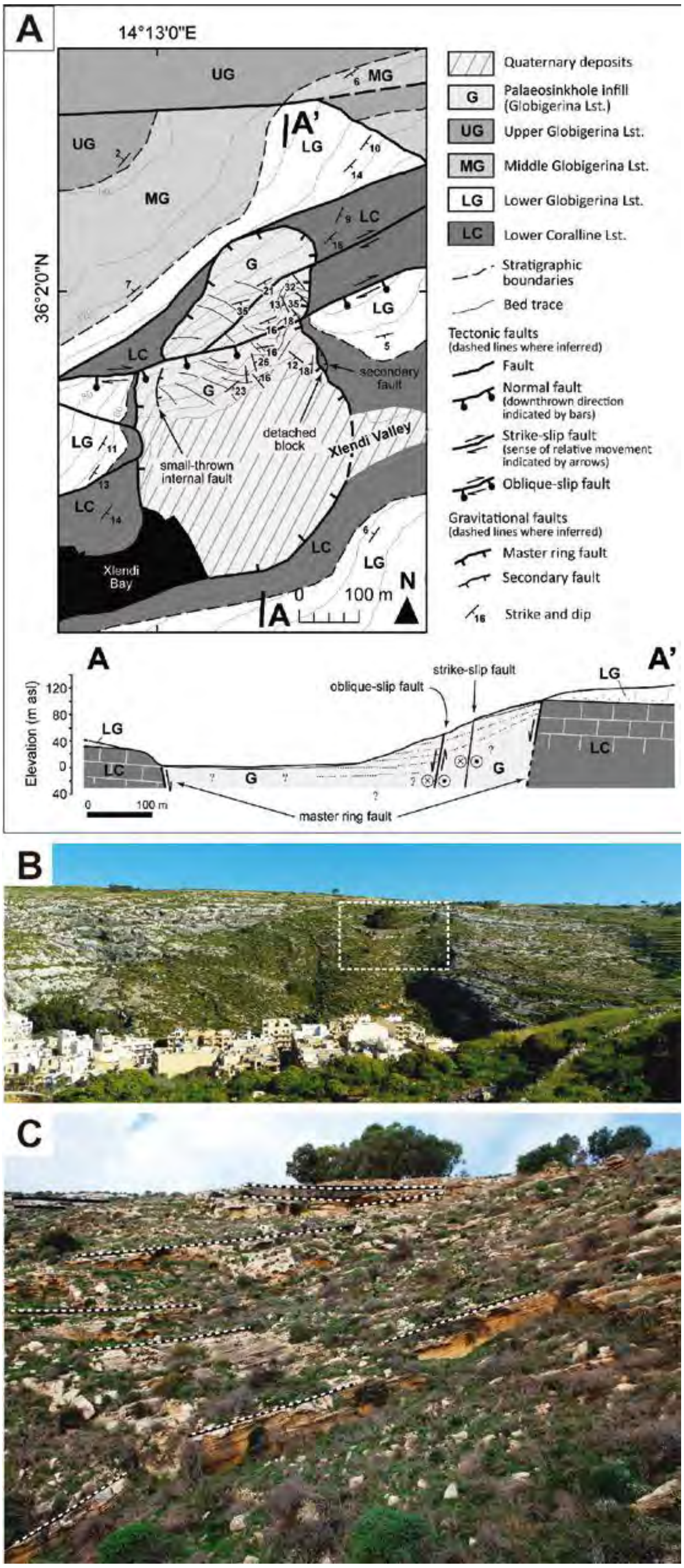

Fig. A2. (A) Detailed geological map and cross-section of the Xlendi palaeosinkhole, offset by oblique dextral-normal tectonic faults. Several small throw radially disposed dip-slip faults in the structure affect the sinkhole infill. (B) General view of the Xlendi collapse from the south. (C) Cumulative wedge-out and progressive upward dip attenuation in the Globigerina Limestone strata of the palaeosinkhole fill (NE margin).

sorted conglomeratic beds, including cobbles and boulders, are thicker and coarser-grained in the palaeosinkhole, whereas the finer-grained units are better sorted and more thinly laminated. The base of the packages of the latter facies typically corresponds to an erosional shallow channel that appears to converge centripetally in the central sector of the subsidence structure. From these features Pedley and Bennet (1985) interpreted the collapse structure as a topographic depression in the sea floor that acted as a sediment trap receiving reworked sediments from the margins and from futher afield to the west. The coarse-grained allochtonous clasts were probably derived from the mass wasting of the scarped margin of the depression and the finer-grained units were deposited in small fans developed within the large submarine sinkhole.

The Xlendi collapse structure is clearly offset in its northern sector by ENE-WSW-trending oblique normal-dextral tectonic faults (Fig. A2.A). In contrast, most of the previous maps implicitly indicate that the collapse is superimposed on the tectonic faults (cf. Pedley 1974, *Fig. 3*; Pedley and Bennet 1985, *Fig. 1*; Oil Exploration Directorate 1993, *Geological Map*). A structural sketch by Illies (1980, *Fig. 14*) properly represents the existing cross-cutting relationship in Xlendi palaeosinkhole, as well as in the paleocollapses of Dwejra area; i.e. gravitational faults offset by tectonic faults. The palaeosinkhole has been offset vertically and laterally on its northern portion by a dextral-normal, down-to the south fault, which splays into at least two strands in the eastern sector of the paleocollapse. The throw related to this fault, together with the unknown depth of the base of the Globigerina Limestone in the palaeosinkhole, make it difficult to estimate the thickness of this unit in the collapse structure and the magnitude of the synsedimentary subsidence. The right-lateral component of the fault is unequivocally observable at the western edge of the palaeosinkhole, where the collapse fault that juxtaposes Lower Coralline Limestone (sinkhole margin) against Globigerina Limestone (sinkhole fill) shows a horizontal separation of about 30 m. Unfortunately, it has not been possible to measure the rake of slickensides in the fault plane, precluding the calculation of the net post-collapse offset on this fault. Most probably, this fault is related to the transtensional neotectonic phase proposed by Gardiner *et al.* (1995) that started in the late Pliocene and generated the North Gozo Graben. Considering a minimum offset of 30 m, and a maximum time span of 3,600 kyr (base of the Late Pliocene), we estimate a minimum slip rate of 0.008 m/kyr, using the paleocollapse as the reference marker.

Qawra palaeosinkhole

Qawra is a steep-sided erosional depression about 365 m in diameter controlled by an annular fault. The depression has a small semicircular lagoon on its northern sector (Figs. A3.A, B). Although the basin is surrounded by scarps or steep slopes, the lagoon is connected to the open sea through a fault-controlled navigable cave more than 100 m long developed in the Lower Coralline Limestone (Fig. A3.B). The margins of the palaeosinkhole are cliffs up to 50 m high in the Lower Coralline Limestone and Lower Globigerina Limestone: the rocks within the collapse are Blue Clay and Upper Globigerina Limestone (Fig. A3) (Pedley, 1974). These cliffs essentially correspond to the main ring fault of the collapse structure exhumed by differential erosion (Fig. A3.B). The Blue Clay and the Upper Globigerina Limestone of the foundered block are more easily eroded than the surrounding Lower Coralline Limestone (Soldati *et al.* 2013). The gully system carved in the Blue Clay that flows into the lagoon indicates that differential excavation in the collapse is mainly related to fluvial incision, and that the excavated sediments have been washed out through the cave that links the lagoon to the sea. The longitudinal profiles of the streams show marked knick points at the margin of the palaeosinkhole attributable to lower incision rate in the Lower Coralline Limestone. On the NE sector of the collapse there is a remnant of a perched mantled pediment sloping towards the main drainage, attesting for a much higher paleobase-level (Fig. A3.B). The pediment deposits mainly consist of poorly-sorted, angular Globigerina and Coralline Limestone clasts, capped by a stage V-VI petrocalcic horizon, according to the morphological classification proposed by Machette (1985) for calcic soils.

Pedley and Bennet (1985) studied the sedimentology of the limited outcrops of Globigerina Limestone associated with the rim of the collapse structure. They correlated these rocks with a condensed sequence of Upper Globigerina Limestone in the surroundings of the palaeosinkhole. In the outcrop located at the foot of the SE rim of the depression they documented Upper Globigerina strata dipping around 20° towards the centre of the collapse. These sediments contain boulders of reworked Lower Globigerina Limestone exceeding 1 m in length (Fig. A3.D). Pedley and Bennet (1985) attributed these allochtonous clasts with drapes in the overlying beds to blocks that fell into the submarine sinkhole from the marginal scarp. This evidence indicates that the sinkhole and its infill were active during deposition of the Globigerina Limestone, and that probably, during some periods, the subsidence depression behaved as a starved basin (subsidence rate > aggradation rate), allowing the development of submarine sinkhole scarps.

Most of the collapse depression is underlain by the Blue Clay, largely masked by vegetation, but where exposed these sediments show a dominant subhorizontal structure. Two samples were collected from this stratigraphic unit for planktonic foraminifera assemblage biostratigraphy. Samples were from the middle sector of the slope in the eastern part of the depression and were vertically about 5 m apart (see location of samples in Figure A3.A). 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.

The Qawra morphostructure is controlled by a subvertical ring fault that juxtaposes Lower Coralline Limestone or Lower Globigerina (SW sector) in the outer zone, against Blue Clay and Upper Globigerina in the foundered block. A vertical displacement of 60 m has been estimated for the collapse, however, the depth of the base of the Blue Clay in the palaeosinkhole is unknown (Table 1). The Lower Coralline Limestone in the margins of the palaeosinkhole change from a subhorizontal attitude to an inward centripetal dip in the vicinity of the collapse fault, suggesting downward rotation by fault-dragging (Fig. A3.C). The restricted Upper Globigerina Limestone outcrops associated with the rim may correspond to fault-dragged slivers bounded between the master and secondary faults. The dominant subhorizontal attitude of the Blue Clay within the collapse structure suggests that it essentially corresponds to a downdropped cyclindrical plug with limited internal deformation. On the NE margin of the depression the gravels of the mantled pediment, capped by a petrocalcic horizon, are juxtaposed against the marginal fault plane developed on the Lower Coralline Limestone. However, it is not clear where this subvertical boundary corresponds to a fault contact (Quaternary fault) or to an erosional free-face contact. It is difficult to unambiguously identify shear fabrics in massive gravels strongly overprinted by pedogenic secondary carbonate (caliche).

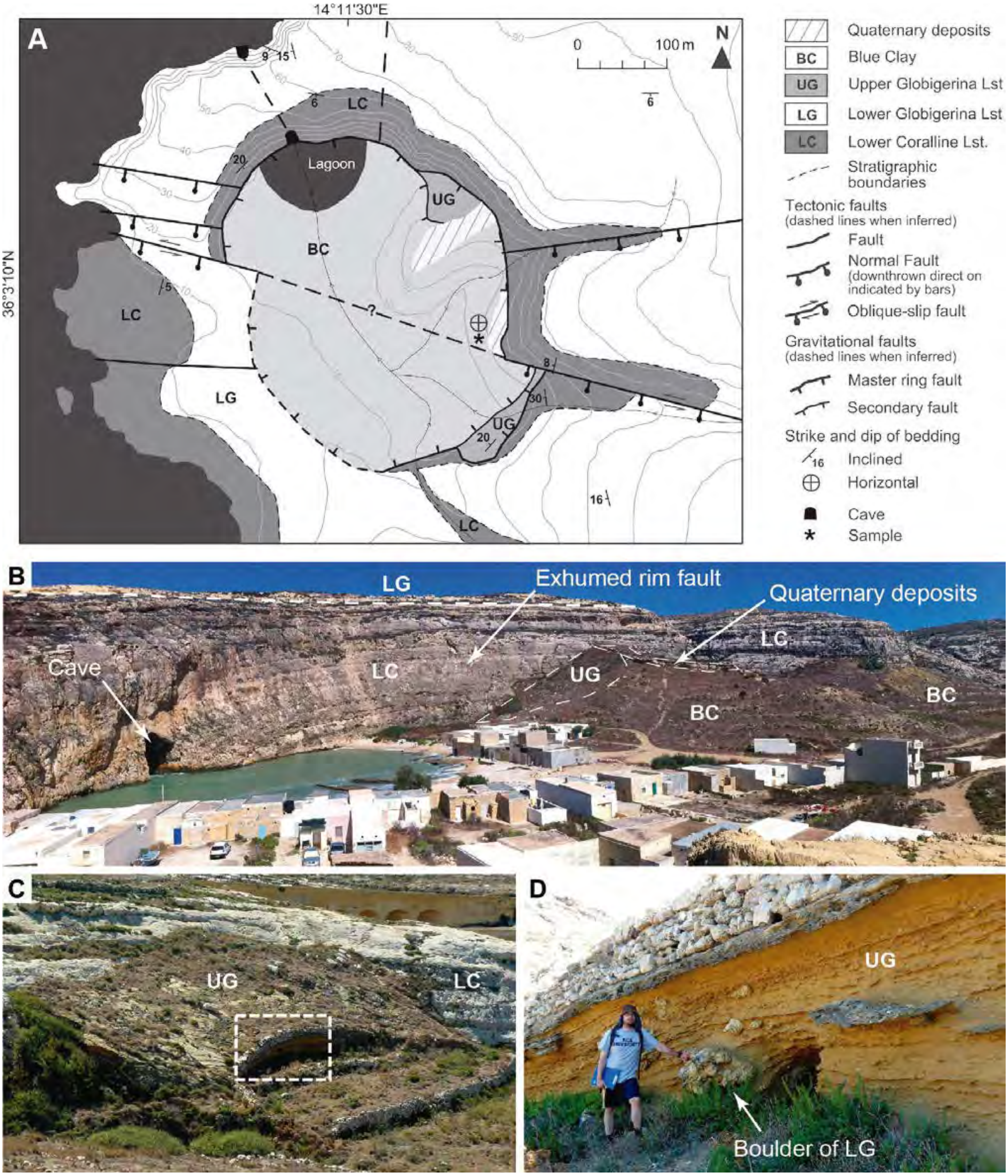

Fig. A3. (A) Detailed geological map of the Qawra palaeosinkhole. (B) View of the NE sector of the erosional depression excavated within the palaeosinkhole. (C) Southeast margin of the collapse, where Upper Globigerina Limestone (vegetated slope) is juxtaposed to Lower Coralline Limestone (bare rock exposure). (D) Boulder of reworked Lower Globigerina Limestone incorporated within the Upper Globigerina deposited in the palaeosinkhole. LC: Lower Coralline Limestone; LG: Lower Globigerina Limestone; UG: Upper Globigerina Limestone.

The paleocollapse structure is offset by a conspicuous ESE-WNW trending oblique fault with sinistral and down-to-the-south displacement components (Fig. A3.A). An excellent exposure of this vertical fault can be found on the SW margin of the collapse, where the outer scarp of the depression shows a conspicuous lateral offset. Here, the exhumed fault plane shows striations and other slickensides with a rake of 15°E. The vertical and left-lateral separations have been estimated at 10 m and 40 m, respectively. This tectonic fault, like those described in Xlendi, is clearly superimposed on the palaeosinkhole, indicating that it corresponds to a recent structure, probably related to the development of the North Gozo Graben since the Late Pliocene (Gardiner *et al.*, 1995). If we assume that the tectonic oblique fault records Late Pliocene-Quaternary displacement (post-3.6 Myr) with a net displacement of 42 m, we estimate a minimum slip rate of 0.01 mm/yr.

Tal Harrax palaeosinkhole

The Tal Harrax erosional depression has been excavated in the largest paleocollapse structure of Gozo, covering approximately 32 ha (Fig. A4). The palaeosinkhole has a NW-SE trending elongated geometry around 600 m long and its NW sector is significantly narrower than the opposite one. These features, similar to those of Xlendi, suggest that the structure may have resulted from the coalescence of two adjoining collapses. The characterisation of this palaeosinkhole is based on very fragmentary information due to poor exposure conditions as the depression is largery covered by terraced fields. Lower Coralline Limestone and Globigerina Limestone have been mapped at the margins of the subsidence structure, whereas the rocks exposed within the paleocollapse include the three members of the Globigerina Limestone and the Blue Clay. The Tal Harrax depression has been excavated by differential erosion by a drainage system, whose trunk channel is hanging about 20 m above the sea level on a cliff of Coralline Limestone overlooking Dwejra Bay.

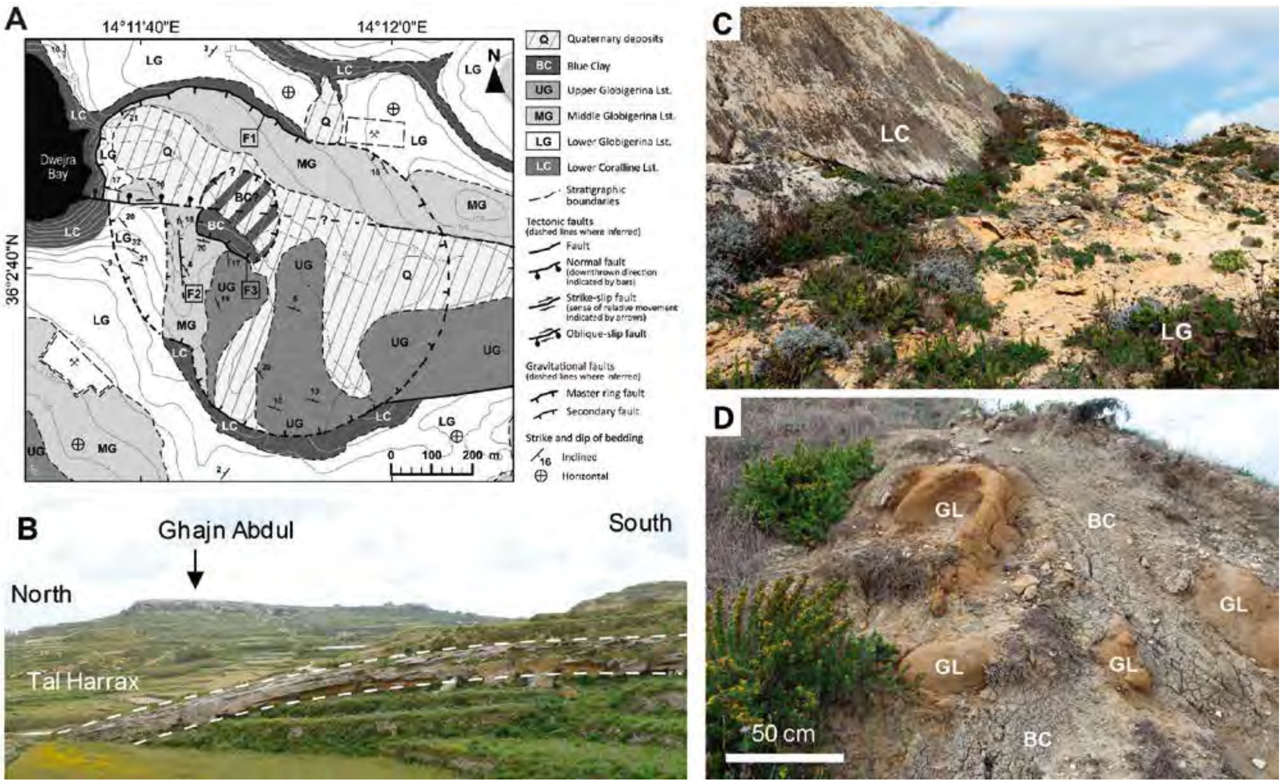

Fig. A4. (A) Detailed geological map of the Tal Harrax palaeosinkhole. (B) Sagging strata of Upper Globigerina Limestone at the southernmost sector of Tal Harrax depression. (C) Tal Harrax rim fault outcrop. LC: Lower Coralline Limestone; LG: Lower Globigerina Limestone. (D) Boulders of Globigerina Limestone (GL) entombed within Blue Clay (BC) deposits at the centre of Tal Harrax structure.

Most of the outcrops are in the western sector of the collapse structure. Here, the lowermost exposed sediments of the Lower Globigerina Limestone comprise pale-grey biomicrites and biosparites with scour and fill structures and phosporite pebbles. This package wedges out from 13 m to 1 m close to the margin of the palaeosinkhole (Pedley 1974). The Lower Phosphorite Conglomerate Bed is clearly recognisable close to the western edge of the collapse. The overlying Middle Globigerina Limestone is a 12 m thick sequence of grey and cream-coloured packstones and wackestones with phosphorite pebbles and abundant bioturbation (Pedley 1974). In the central sector of the collapse, a normal fault (F3 in Fig. A4.A) juxtaposes Globigerina Limestone in the footwall, against Blue Clay in the downthrown block, indicating that there should be an inner ring fault that has foundered a plug of Blue Clay (Pedley, 1974). The restricted outcrop of Blue Clay includes conspicuous rounded decimetre- to meter-sized boulders of reworked Globigerina Limestone, interpreted by Pedley (1974) as blocks fallen on unconsolidated clays from an adjacent submarine sinkhole scarp (Fig. A4.D). This evidence, together with the thickness changes observed in the Globigerina Limestone, indicate that the palaeosinkhole was active over a long time span (ca. 10 Myr) in the Miocene, during deposition of the Globigerina Limestone and the Blue Clay.

The exposed Blue Clay 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 and 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)*. The elevation difference between the top of the Blue Clay in Tal Harrax and its surroundings indicates that vertical displacement may have reached about 100 m in the centre of this collapse structure (Pedley 1974). Most probably, a great part of this displacement has occurred after the deposition of the Blue Clay (post-sedimentary).

The Miocene sediments within the elongated collapse structure show a general inward dip towards the axial zone (Fig. A4.B), where the strata tend to be subhorizontal. The dip of the strata of the Lower Globigerina and Middle Globigerina seem to indicate a change in the position of the depocentre of the structural basin towards the SE. This pattern may be related to the coalescence of two depressions during deposition of the Globigerina Limestone and/or the migration of the subsidence centre through time.

The outer ring fault of the collapse can be observed in the NW margin of the depression, where differential erosion of the hanging-wall sediments has exhumed the curved gravitational failure plane, with an inward dip of 54° and striations indicative of dip-slip displacement (Fig. A4.C). The relatively low dip of the collapse fault at this site, located next to a recent tectonic fault and on the crest of the monocline, may be related to post-collapse deformation (fault-related tilting and/or monoclonal folding). A minimum vertical separation of 50 m has been estimated for this marginal collapse fault. The edge of the collapse structure in its southern and eastern sectors has been inferred from sharp changes in lithology and dip, plus slope breaks attributable to concealed faults. Small-throw down-to-the-east normal faults have been mapped in the SW sector of the depression (Fig. A4.A). The plane of fault F2 is vertical and shows slickensides indicative of gravitational dip-slip displacement. The exposures on the western sector of the palaeosinkhole, next to Dwejra Bay, clearly show that the collapse structure is offset by an E-W oblique sinistral-normal fault. The exhumed subvertical fault plane shows slickensides with a pitch of 36°W and crescentic fractures indicative of left lateral and down-to-the north displacement components. The vertical and horizontal separations have been estimated at 12 m and 16 m, respectively.

Dwejra North and Dwejra Bay palaeosinkholes

Dwejra North and Dwejra Bay are rounded bays each abour 350 m in diameter, with steep Lower Coralline Limestone cliffs, resulting from differential erosion of the collapsed sediments within palaeosinkholes (Fig. A5). Probably, selective erosion was particularly important during sea level lowstands (e.g. Last Glacial Maximum), when the palaeosinkholes were situated on land. Presumably, during that stage, the eroded sediments were evacuated by east-flowing drainages flowing through water gaps controlled by E-W trending faults. The erosional depressions were submerged by the sea during the Flandrian transgression at ca. 7-5 ka (Soldati *et al.* 2013).

Dwejra Bay, a few meters west of Tal Harrax depression, is a subcircular bay surrounded by nearly vertical cliffs up to 60 m high underlain by Lower Coralline Limestone. These scarps are essentially the exhumed plane of the ring fault that controls the collapse structure. The sea-facing western margin of the collapse depression shows two gaps with a prominent islet in between, called Fungus Rock. The northern margin shows a wave-cut platform eroded in Lower Coralline Limestone and sloping towards the sea.

This collapse structure is located in the dipping limb of the arcuate west-facing monocline; the Lower Coralline Limestone shows a general NNW dip clearly observable at Fungus Rock. The ENE-WSW trending oblique fault mapped in Tal Harrax depression, with sinistral and down-to-the-north displacement components, also affects the Dwejra Bay collapse structure, shown by the lateral offset of the cliff on the eastern margin. A digital elevation model of the bottom of Dwejra Bay has been generated with LiDAR data obtained with a spatial resolution of 1 m. These data suggest that the bottom of the submerged erosional depression has a very irregular topography and an annular ridge around 190 m in diameter (Fig. A5).

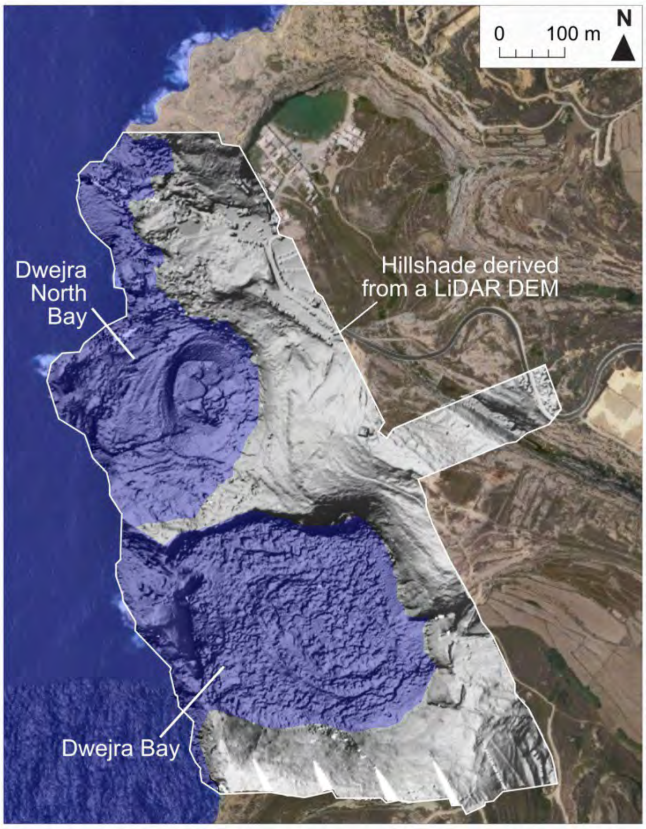

Fig. A5. Digital elevation model generated from LiDAR data, showing the topography of the sea floor at Dwejra North Bay and Dwejra Bay. Note the steep-sided enclosed depression in the NE sector of the bay controlled by the collapse structure. The bottom of the closed depression has a marginal trough and a protruding central sector with blocky appearance.

Dwejra North Bay is a semicircular bay with low-relief cliffs of Lower Coralline Limestone. Structural benches have been developed by differential erosion at the contact between the Lower Coralline Limestone and the overlying Globigerina Limestone. Although the western margin of the collapse structure has been largely removed by erosion, it can be inferred on the basis of a partially emerged ridge of Lower Coralline Limestone. The LiDAR-based digital elevation model has allowed the discovery of interesting features (Fig. A5). The floor of the bay shows a nested enclosed depression 160 m in diameter and 4 m deep in the NE sector of the collapse structure. The bottom of this steep-sided submarine sinkhole shows a peculiar marginal trough at the foot of the scarp, and a protruding central zone with blocky appearance. The margin of this fresh-looking hole seems to be offset by an ENE-WSW oblique dextral fault. To our knowledge, this is the only collapse structure of the Island of Gozo which shows true sinkhole morphology (closed depression). This suggests that some collapse structures may have been affected by recent activity: if it had been inactive for a long time evidence of dissection or sediment fill might be expected. Another alternative would be the generation of a closed depression by differential wave erosion of soft sediments (e.g., Blue Clay).

Wardija Point and Wied il-Mielah palaeosinkholes

At Wardija Point, a prominent headland in the southwestern edge of Gozo, there is a palaeosinkhole 60 m in diameter, expressed as a protruding hill about 10 m above the local relief (Fig. A6.A). The exposed rocks surrounding the paleocollapse correspond to Middle Globigerina Limestone. The hill in the foundered block is formed of Upper Coralline Limestone comprising massive peloidal carbonate mudstones with abundant rhodoliths and molluscs. A minimum throw of 50 m has been estimated for this structure based on the estimated eroded thickness of Globigerina Limestone and the thickness of Blue Clay. The cartographic relationships observed in this structure indicate that the collapse was active after the deposition of the Upper Coralline Limestone in Pliocene and probably Quaternary times.

A similar subcircular paleocollapse structure with positive relief occurs on the west margin of Wied il-Mielah valley, 2.5 km NE of the Il-Maxell palaeosinkhole (Fig. A6.B). Here, the Upper Coralline Limestone has foundered within the stratigraphically lower Globigerina Limestone. The collapse fault is concealed by terraced crop fields, but it can be inferred by aerial photograph interpretation as an annular structure around 180 m in diameter. A post-Upper Coralline Limestone minimum throw of 60 m has been estimated for this gravitational structure using the same criteria as in Wardija Point palaeosinkhole.

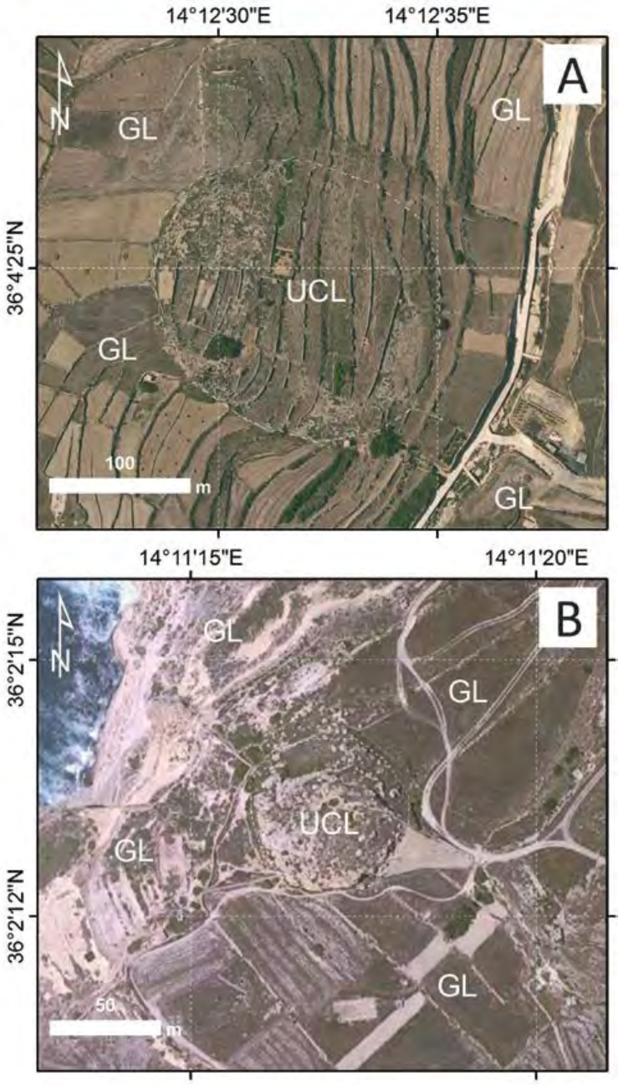

Fig. A6. Aerial orthoimages of Wied il-Mielah (A) and Wardija Point (B) palaeosinkholes. UCL: Upper Coralline Limestone; GL: Globigerina Limestone.

Ghajn Abdul palaeosinkhole

In the northwest Gozo the exposed bedrock consists mainly of Globigerina Limestone, except for isolated mesas and buttes of Blue Clay overlain by a caprock of Upper Coralline Limestone. Ghajn Abdul is the westernmost mesa capped by cliff-forming Upper Coralline Limestone (Fig. A7). It has a slightly elongated geometry about 400 m along its major axials. An E-W trending, down-to-the-south normal tectonic fault offsets the Miocene succession just north of the mesa (Fig. A7.A). Ghajn Abdul was interpreted as a palaeosinkhole (Pedley, 1974), currently expressed in the landscape with a inverted positive relief resulting from differential erosion leaving the collapsed more resistant sediments upstanding above the surrounding rocks (O il Exploration Directorate, 1993). The palaeosinkhole interpretation is based on the following evidence: (1) In Ghajn Abdul mesa, the thickness of the Upper Coralline Limestone is more than seven times thicker than in the nearby mesas. Such thickness difference cannot be explained by tectonic faulting or folding. (2) The Upper Coralline Limestone strata show centripetal dips towards the centre of the mesa forming a basin structure. Dips are commonly higher than 20° and locally reach more than 40° (Fig. A7.A). (3) Cartographic relationships between the Blue Clay Formation and the Upper Coralline Limestone Formation indicate the presence of a concealed annular fault around the mesa that has controlled the collapse of the latter into the former (Fig. A7.A, B).

Four stratigraphic sections were recorded in the Miocene sediments of Ghajn Abdul and an adjacent mesa to the east (Fig. A7.C). Although they are located just 80 m apart, the successions in the two mesas show different carbonate facies. The stratigraphic logs start in the upper part of the Globigerina Limestone and reach the uppermost exposed sediments of the Upper Coralline Limestone in each mesa. Sections 1 to 3 from Ghajn Abdul mesa cross the boundary between the palaeosinkhole and the surrounding deposits; consequently they include sediments located both outside the palaeosinkhole (Globigerina Limestone and Blue Clay), and inside it (Upper Coralline Limestone). This explains the lower and variable thickness (3-25 m) of the Blue Clay in Ghajn Abdul, where it has been partially removed by erosion. Conversely, in the adjacent mesa there is a complete 27-m-thick Blue Clay sequence overlain and protected by the Upper Coralline Limestone. The lowest exposed beds of the Upper Coralline Limestone in Ghajn Abdul are in the southern sector of the mesa, where erosion of the Blue Clay has been greatest (see cross-section in Fig. A7.B). Grainstone and packstone beds dip 45-60º towards the center of the mesa and include sparse meter-sized blocks of reefal origin, including biocalcarenite containing large coral colonies, abundant pectinids, gastropods and oysters (Fig. A8.B). This unit shows load casts and contorted bedding associated with the allochtonous boulders. This bouldery unit is overlain by white, low-angle cross-bedded packstones and grainstones forming sets 5 to 15 m thick. These layers contain bioclasts of coralline algae, molluscs, echinoids and small scattered rhodoliths, all overlain by a planar-bedded unit. The sequence continues with a 1 to 5 m-thick chalky limestone, followed by a highly bioturbated carbonate mudstone. At the top, there is a 5 to 10 m-thick bioturbated massive limestone containing miliolids, coralline algal fragments and molluscs (Fig. A8.A).

Subsidence in the Ghajn Abdul palaeosinkhole has been accommodated by dip-slip displacement on the marginal collapse fault, together with sagging in the foundered block. The extensive exposures in a large quarry excavated in the northeast sector of the mesa show a sagging not affected by secondary faulting.

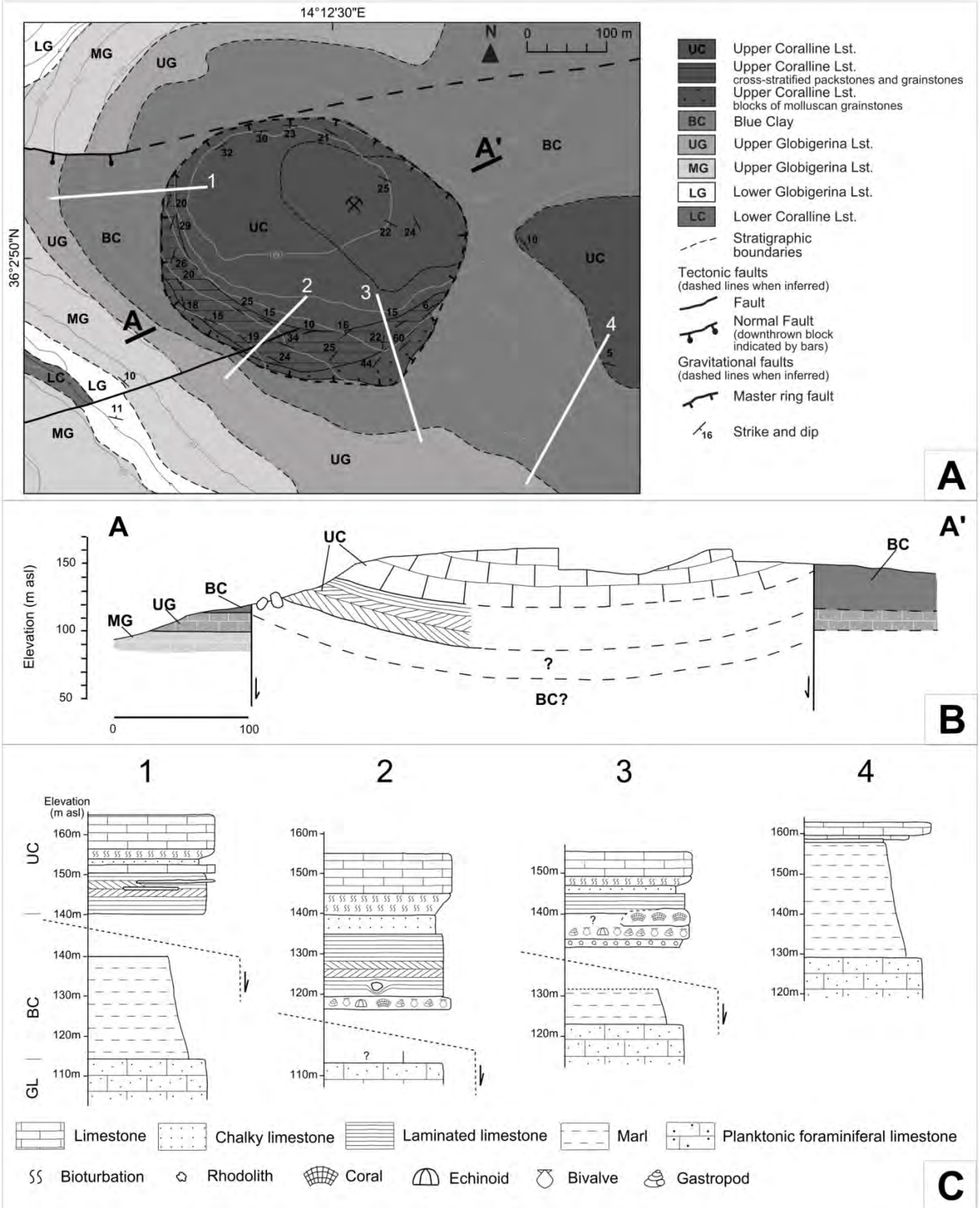

Fig. A7. Detailed geological map of the Ghajn Abdul palaeosinkhole (A) and cross-section (B). The numbers in the geological map indicate the stratigraphic sections shown in C. (C) Stratigraphic sections recorded in Ghajn Abdul palaeosinkhole (1, 2 and 3) and in the adjacent mesa.

An allochtonous boulder associated with soft-sediment deformation observed in the Upper Coralline Limestone, next to the inferred collapse fault, may be interpreted as blocks fallen from a nearby submarine sinkhole scarp, as it has been proposed in Qawra and Tal Harrax (Pedley, 1974). This suggests that subsidence was active during deposition of the

Upper Coralline Limestone. Moreover, the accommodation space generated by dissolution-induced subsidence in the sea floor provides a satisfactory explanation for the local sedimentological changes observed in Ghajn Abdul. The high dip of the strata in the basin structure observed within the collapse block also indicates that there has been some postsedimentary subsidence.

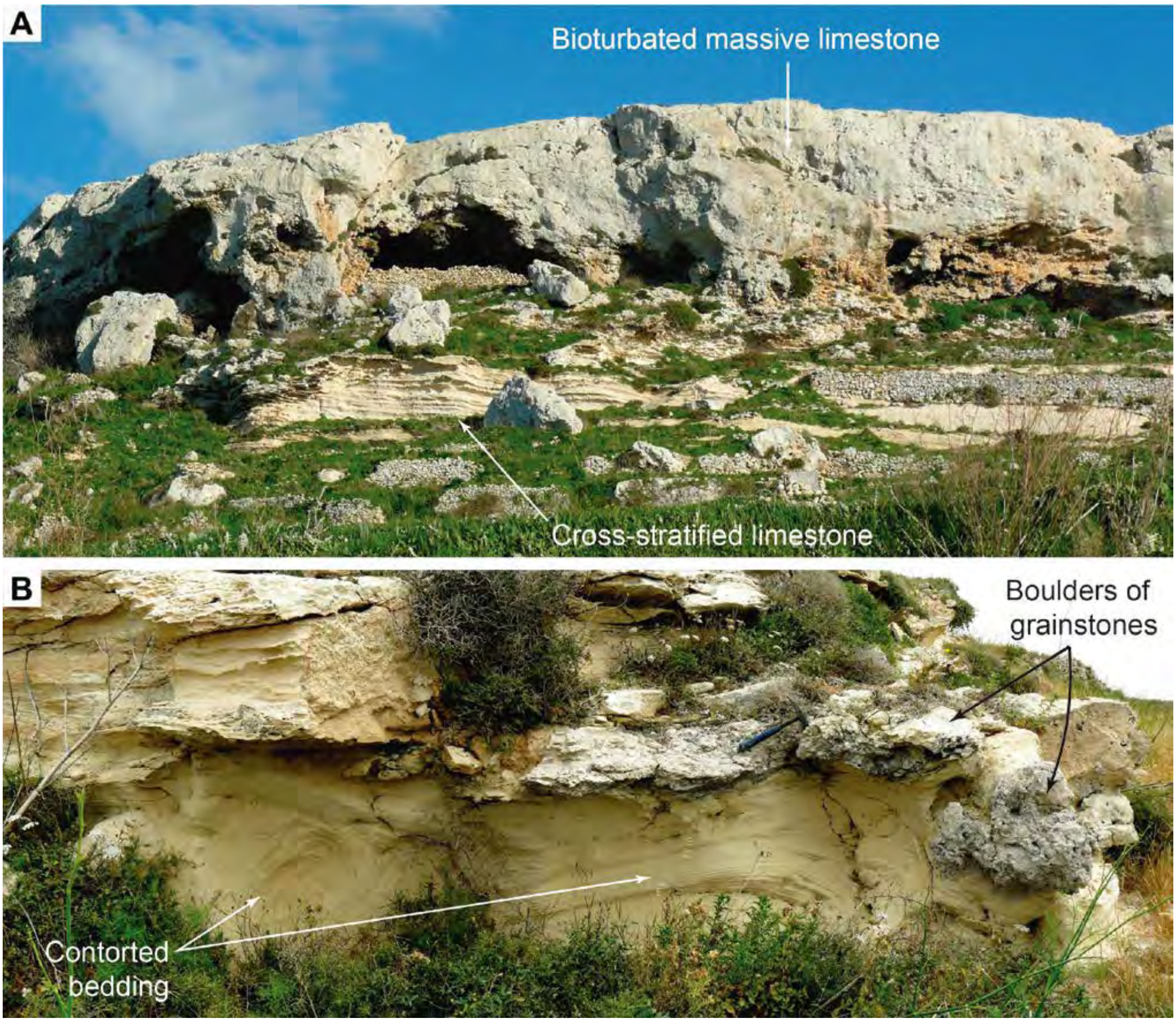

Fig. A8. (A) Upper part of Ghajn Abdul mesa capped by Upper Coralline Limestone. Note the low-angle cross stratified packstones and grainstones overlain by bioturbated massive limestone at the top. (B) Load casts and contorted bedding in the cross stratified packstones and grainstones associated with large meter-sized allochtonous boulders of grainstones containing pectinids, echinoderms, oysters and gastropods.