COBISS: 1.01

THE PROBABLE KARST ORIGIN AND EVOLUTION OF THE VENDICARI COASTAL LAKE SYSTEM (SE SICILY, ITALY)

VERJETNI KRAŠKI IZVOR IN RAZVOJ OBALNEGA JESERSKEGA SISTEMA VENDICARI (JV SICILIJA, ITALIJA)

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Abstract UDC 551.435.83(450.82)

F. Javier Gracia, Francesco Geremia, Sandro Privitera & Concetto Amore: The probable karst origin and evolution of the Vendicari coastal lake system (SE Sicily, Italy)

The Vendicari coastal lake system (SE Sicily) presents several geomorphic characteristics, which suggest it was originated as a part of a 6 km long karst polje during the Late Pleistocene sea level lowstand. Exhumed cryptokarst karren and terraced concentric surfaces point to this working hypothesis. The generation of this depression could have been favoured by the low to moderate neotectonic activity in the zone, which consisted in slight uplifting and subsequent fracturing. Open joints in the Vendicari Pleistocene carbonates show a radial outline with the prevalence of NNW-SSE discontinuities. Once formed, polje evolution would have consisted in a progressive compartmentalisation and splitting into several polje bottoms, some of which form a part of the present Vendicari lake system and are surrounded by stepped corrosion surfaces. The postglacial sea level rise had drowned most part of the original polje, which can be still recognized in the inner continental shelf. Sea level stabilization after the Holocene eustatic maximum favoured the development of a beach barrier, which generated additional coastal lakes of lagoonal type.

Keywords: Coastal lake, Karst, Polje, Sea level changes, Sicily.

Izvleček UDK 551.435.83(450.82)

Francisco Javier Gracia Prieto, Francesco Geremia, Sandro Privitera & Concetto Amore: Verjetni kraški izvor in razvoj obalnega jezerskega sistema Vendicari (JV Sicilija, Italija)

Obalni jezerski sistem Vendicari (JV Sicilija) predstavlja več geomorfoloških značilnosti, ki kažejo, da je sistem nastal kot del 6 km dolgega kraškega polja med znižanjem gladine morja v poznem Pleistocenu. Razkrite škraplje pokritega krasa in uravnana koncentrična površja kažejo na to delovno hipotezo. Razvoj te depresije bi bil lahko povezan z nizko do zmerno neotektonsko aktivnostjo, ki je zajemala manjša dviganja in posledične razpoke. Odprte razpoke v Pleistocenskih karbonatih področja Vendicari kažejo radialen načrt s prevladujočimi prekinitvami v smeri SSZ-JJV. Ko je polje nastalo, je njegov razvoj zajemal postopno ločevanje in delitev v več polj. Nekatera polja tvorijo današnji obalni sistem Vendicari in so obkrožena s stopničastimi korozijskimi površinami. Dvig morja po glacialnem obdobju je potopil večji del prvotnega polja, ki ga še lahko zasledimo v notranjem kontinentalnem grebenu. Stabilizacija nivoja morja po maksimalnem dvigu vode je bila ugodna za razvoj obalne pregrade, ki je povzročila nastanek dodatnih obalnih jezer lagunskega tipa.

Ključne besede: obalno jezero, kras, polje, spreminjanje nivoja morja, Sicilija.

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Received/Prejeto: 04.07.2014

INTRODUCTION

Investigations relating coastal and non-coastal karst evolution are increasing in the last decade, especially in Mediterranean coastal environments (Nicod 1986; Bruno *et al.* 2008; De Waele *et al.* 2011; Canora *et al.* 2012). One of the most important difficulties when studying karst forms in coastal environments lies in the fluctuating location of their base level, represented by the sea level. During the Quaternary, 70 % of the time the sea level was between −30 and −120 m with respect to the present sea level (Purdy & Winter 2001), which means that many forms presently submerged in the inner continental shelf were originally generated under subaerial conditions (Surić 2002; Van Hengstum *et al.* 2011). In karst environments typical submerged forms are marine caves, quite common in Mediterranean coasts, or valleys whose bottoms lie below the present sea level (Gams 2005). The analysis of all these submerged forms supply valuable information on the palaeogeographic evolution of coasts, extent of the area affected by karst processes and by sea level fluctuations, and duration of the lowstand episodes during Quaternary times, and is also useful for evaluating the submerged geological heritage (Taviani *et al.* 2012). In Sicily these outcrops are present throughout the coastal zone and occupy much of the NW and SE sides of the island (Di Maggio *et al.* 2012). However, no descriptions have been made on the interactions between the littoral karst and marine processes and coastal evolution, except in NW Sicily (Ruggieri & De Waele 2014).

The Vendicari area, situated in SE Sicily (36°47'N – 15°05'E), represents a suitable area to study the interaction of karst and marine processes. The site area is in a microtidal, wave-dominated and bedrock-confined coastal environment, where there are evidences of karst processes in Quaternary carbonate shore-platforms and eolianites. It is also characterized by the presence of a sandy dune-beach system *(Bay of Vendicari)* and a coastal lacustrine-palustrine system (Vendicari coastal lakes, locally called "Pantani di Vendicari") with three presently flooded coastal lakes and four ancient coastal wetlands (Fig. 1). In 1984 the Vendicari area was declared "Oriented Natural Reserve" by the Regional Government of Sicily, with the objective of safeguarding migratory and native wildfowl. The "Oasi faunistica di Vendicari" Regional Natural Reserve encompasses 1512 ha, from which 575 are included in an Integral Reserve extended about 8 km along the coast and between 200 and 1300 m inland. The site is also designated as a Special Protection Area under the EC Birds Directive (79/409/EEC) and on 1989 it was included in the Ramsar List of wetlands of international importance.

The aim of this research is to investigate the origin and evolution of the Vendicari area, using historical maps, aerial photos and field observations. The possible origin of the depressions is related to karst processes. Bathymetric information is also used to evaluate the submarine extent of the karst landforms in the area. The

Fig. 1: Location of Vendicari coastal wetlands and lakes. Elaborated from Google Earth (2013).

evolution of the lake/karst system is established in relation to Late Quaternary sea level changes. This contribution presents a working hypothesis by which different indirect evidences point to the generation of a polje during the Late Quaternary, controlled by sea level changes and presently drowned in its most part.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

Detailed geological and geomorphological maps of the zone (Figs. 2 and 3) were elaborated through aerial photointerpretation and field work. Two sets of aerial photographs were used for this purpose, one from the Società Aerofotogrammetrica Siciliana, taken in 1977 at 1:4000 scale, and the other from the Società Riprese Aeree di Parma, taken in 1987 at 1:10,600 scale. Data were represented upon an original topographic base at a 1:4000 scale. Bathymetric data were obtained from the nautic chart no. 21 (Da Capo Passero a Capo S. Croce, scale 1:100,000), elaborated by the Italian Istituto Idrografico della Marina.

The Vendicari area is located in the northern border of the Ispica-Capo Passero depression at the South East part of the Hyblean Plateau, a carbonate platform constituted by Late Triassic to Early Pleistocene sediments with some interbedded volcanic levels. It forms part of the northern margin of Africa plate, which is to the North bounded by the thrust front of the allochthonous units. To the East, it is cut off by the Malta escarpment, a large fault system separating the continental shelf from the thinned crust underlying the Ionian Sea (Grasso *et al*. 1992). The Hyblean Plateau includes a wide variety of karst forms (Di Maggio *et al.* 2012), mostly studied by local speleological groups (Ruggieri *et al.* 2009; Ruggieri & Carbone 2010; among others).

The detailed stratigraphy of the Vendicari area is described in Ruggieri (1959) and Lentini *et al*. (1984). Although during the Early Pliocene the Hyblean Plateau was largely emerged, pelagic chalks (Trubi formation) were deposited all around the Vendicari area (Fig. 2). This unit was subsequently folded into gentle anticlines with axial planes oriented around 60°N and normal faults trending 150°N, perpendicularly to the local fold axes (Grasso *et al*. 1992). During Early Pleistocene times biocalcarenites were deposited in shallow marine basins, being afterwards raised up to 150 m along the margins of the depression (Grasso *et al.* 1992). The Quaternary sediments were formed during two main sedimentary cycles. The first one took place in the Lower-Middle Pleistocene and is represented by homogeneously lithified calcarenites mainly composed of fine and medium carbonate particles. The second cycle, covering the Late Pleistocene, is represented by yellow calcarenites composed of medium carbonate particles with typical aeolian oblique and cross-bedded laminae, sometimes disturbed by collapse structures. These are separated from the precedent cycle by lacustrine deposits capped by a palaeosoil at about 1–2 m above the sea. The top of this second sedimentary cycle appears at + 16 m, a height fairly similar to those related to Tyrrhenian deposits recognized along the SE coast of Sicily (Antonioli *et al*. 2006).

The Quaternary tectonic evolution of the Southeast Hyblean Plateau, as well as its fault geometry, were analysed by Adam *et al.* (2000) and Monaco & Tortorici (2000). Since Pliocene times the Hyblean Plateau has suffered brittle deformation in the form of a certain vertical tectonic motion and limited uplift, mainly associated with the activity of some transpressional faults (Antonioli *et al*. 2006). Middle Pleistocene calcarenites onlap the Trubi, and are softly folded (Grasso *et al.* 1992). Deformational processes between Early Pliocene and Late Pleistocene (Tyrrhenian) times in the area were dominated by a well developed trending fault system (Grasso *et al*. 1992): NNE–SSW normal faults control the Ionian coast of Eastern Sicily and continental shelf, while NNW–SSE faults characterize the regional Malta escarpment, among others.

The landscape of the outermost sector of South East Sicily is flat and slowly inclined in direction to the sea, with several fluvial terraces along the Roveto and Saia Scirbia river valleys (Figs. 1 and 2). Their hydrographic basins are 7 km^2 and 35 km^2, respectively. These streams are often dry in the summer months and occasionally communicate with the sea through the coastal lacustrine-palustrine system. Holocene to recent deposits in the area are represented by palustrine and lacustrine deposits in the Pantani sites and mainly a sandy barrier beach with an extensive coastal dune system. In the study area, there are also evidences of erosional forms cut into carbonate units such as cliffs, caves and shore platforms and mainly karst depressions incised in carbonate-cemented marine and aeolian sandstones.

The climate is typically Mediterranean (semi-arid and steppe type) and controlled by seasonal weather patterns: temperate-arid with concentrated rainfall from October to March and insufficient rainfall from April to

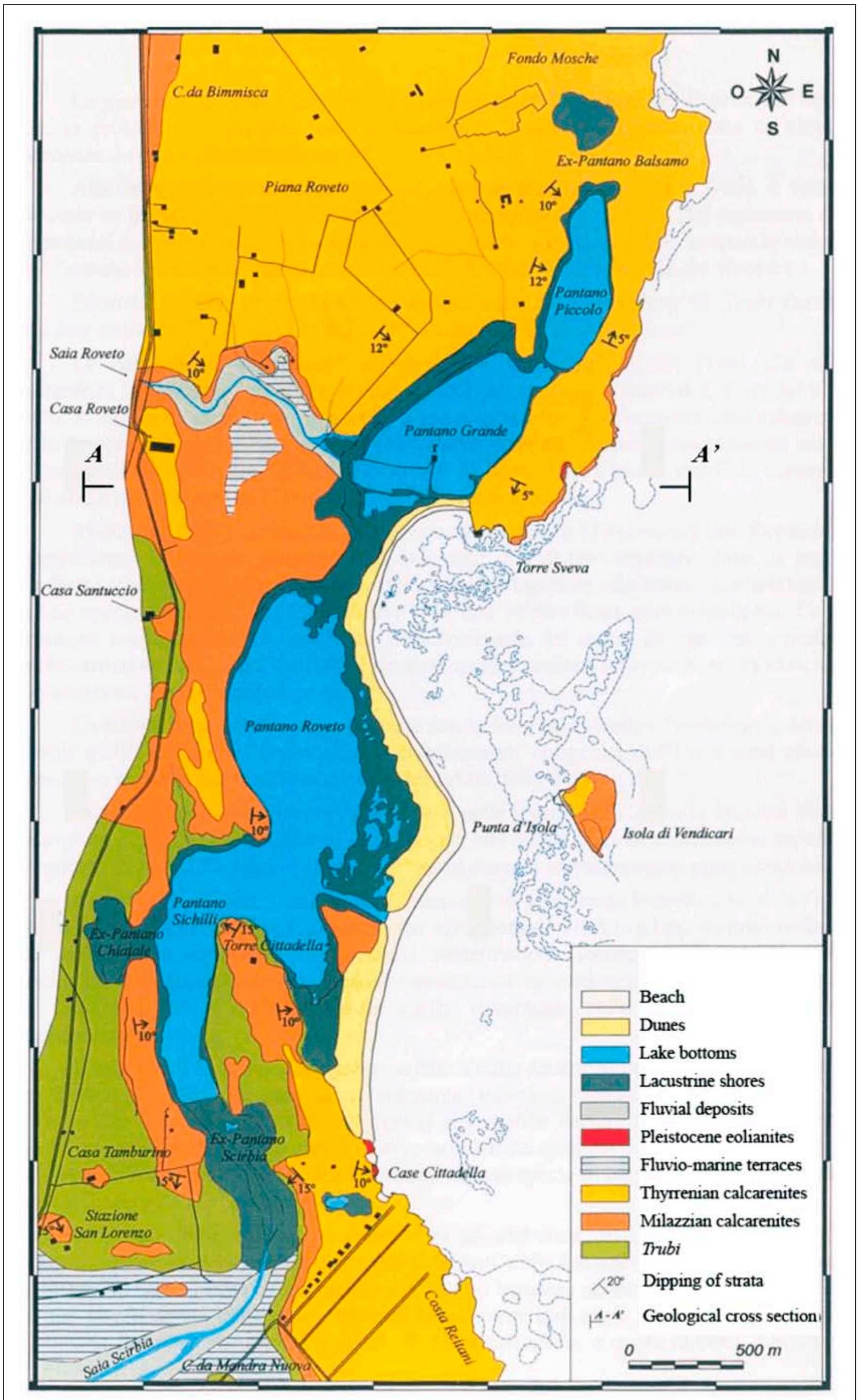

Fig. 2: Geological map of Vendicari area.

September. At the meteorological station of Cozzo Spadaro (Regione Siciliana 1998), located 10 km South of Vendicari, mean annual temperature and precipitation are 18 °C and 400 mm respectively. The Tellàro river is the main source of sediments to the coastal system. It is one of the most important rivers in South Sicily, more than 40 km long, and its mouth is located just 2 km to the north of Vendicari. It forms part of a set of long and deep fluviokarst canyons that strike along the main regional gradients (Di Maggio *et al.* 2012).

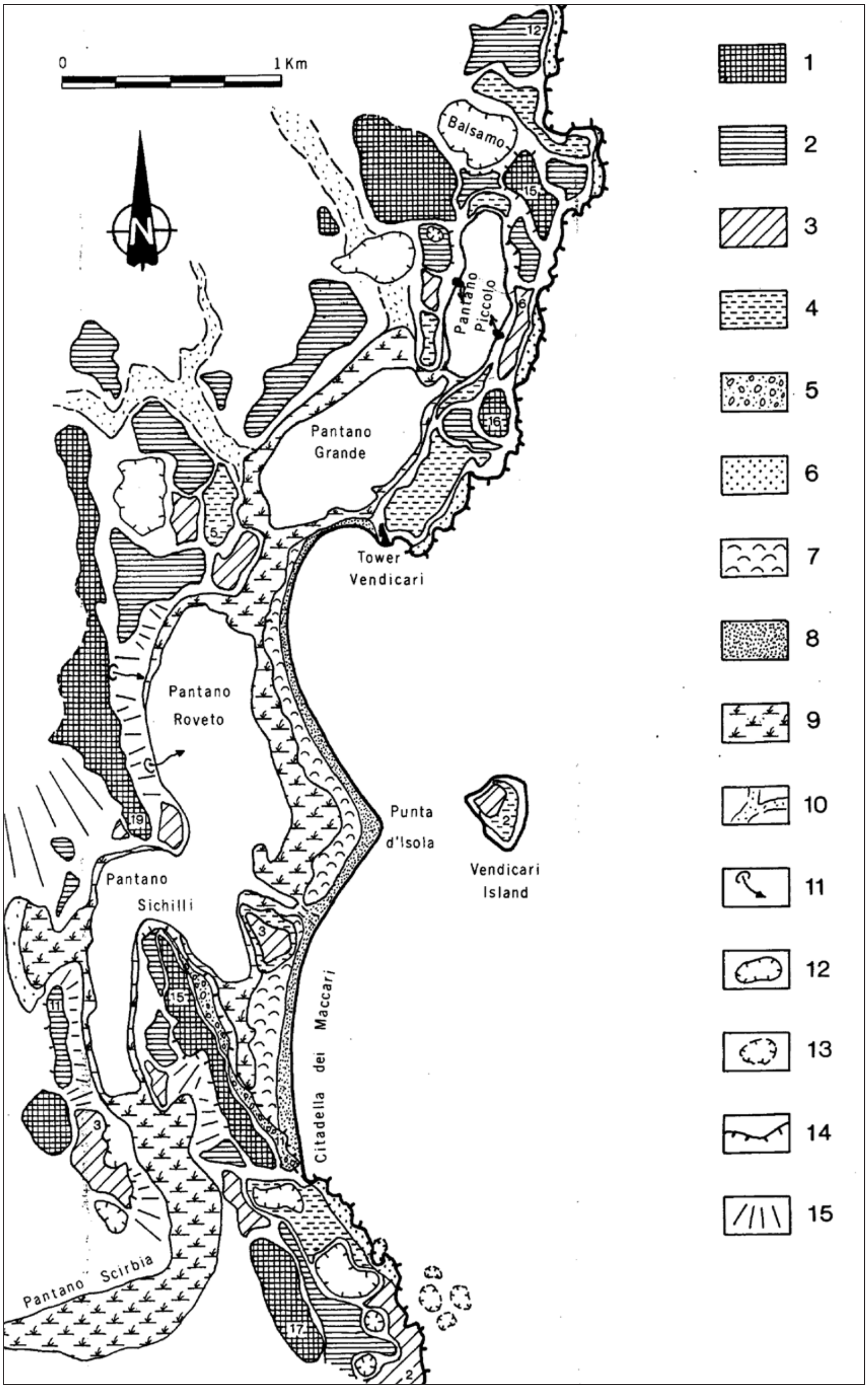

Fig. 3: Geomorphological map of Vendicari coast. Legend: 1-Karst corrosion surface C1; 2- Surface C2; 3-Surface C3; 4-Surface C4; 5-Thyrrenian eolianites; 6-Hanging shore platform (Flandrian?); 7-Dune ridges; 8-Beach; 9-Marshes; 10-Flat bottomed valleys; 11-Spring; 12-Doline; 13-Submerged doline; 14-Escarpment; 15-Gentle slope. Numbers refer to meters above the sea.

The Vendicari coastal lacustrine-palustrine system is composed by seven, ancient and present coastal wetlands and lakes segmented and distributed parallel to the coastline (Fig. 3), with shallow and very flat bottoms. Three of them are permanently flooded although seasonally fluctuating wetlands locally used as salt extraction areas since Greek-Roman times. The northern coastal lagoons (Pantano Piccolo and Pantano Grande) and other ancient lakes and ponds (like Balsamo lake, North of Pantano Piccolo) are restricted from the sea by rocky carbonate ridges about 15–16 m high (Fig. 4), rich of karst meso and microforms (karren, grikes, dolines, etc.). Pantano Scirbia, Sichilli and Roveto form an estuarine depression related to Saia Scirbia River, partly seg-

Tab. 1: Main morphometric characteristics of the Vendicari coastal lakes.

Coastal Lakes	***Balsamo***	***Piccolo***	***Grande***	***Roveto Sichilli***	***Scirbia***	***Chiatale***	***Cittadella***
Surface Area (ha)	4.4	15.6	34	103.5	14	4.4	0.4
Altitude (m)	4.2	0.0	0.0	0.0	0.70	0.70	1.10
Lake shape	Subcircular	Elliptical	Elliptical	Elliptical–Dendritic	Dendritic	Elliptical	Subcircular
Max length (m)	288	775	725	1750	646	375	99
Max width (m)	250	265	427	650	198	162	51
Max depth (m)	0	1	0.5	1	0.5	0	0

Fig. 4: A view of Pantano Piccolo lake to the North from Tower Vendicari area. Note the planated surface developed on carbonates between the lake and the sea.

mented by calcareous ridges. It is a blind estuary, separated from the sea by a cuspate sand barrier. The main morphometric characteristics of these transitional areas are synthesized in Tab. 1.

Most lakes in the Vendicari wetland system are interconnected. Lakes Grande and Piccolo are connected though a narrow pass developed upon the calcareous substratum. Lakes Grande and Roveto are separated by calcareous hills and by marshes. Roverto, Sichilli and Scirbia form part of a single lacustrine depression, partly segmented by low calcareous ridges. Completely dry lakes appear both to the North of Piccolo Lake (Balsamo Lake) and to the South of Sichilli wetland. Their bottoms

Fig. 5: The trace of a littoral freshwater spring can be seen on the western coast of Pantano Roveto lake. Vertical aerial photography taken in 1987, scale 1:10,600 (Società Aerofotogrammetrica Siciliana 1988).

hang some meters above sea level and are separated from the present lakes by calcareous planated ridges.

Water supply to the lakes comes from runoff and from underground fluxes. Pantano Grande lake receives fresh water incomes through several springs located in its western side, both at the rocky slope and on the lacustrine shore (Fig. 5). Lake water levels are linked to the present sea level: there is direct hydrogeological connection between lakes Grande-Roveto-Sichilli and the sea through the Vendicari sandy barrier, while between Pantano Piccolo Lake and the sea water connection is made through fissures and fractures in the intervening rocky ridges.

At present Vendicari lake levels do not fluctuate significantly and their depth is always lesser than 1 m. Sedimentology of the lacustrine sediments of the lakes and recent environmental evolution were previously studied by Amore *et al.* (1994), Amore & Geremia (2001) and Geremia (2000).

RESULTS

The geomorphological map reveals the presence of four stepped planation surfaces with a rough concentric distribution about the bottoms of Sichilli, Grande and Piccolo lakes (Fig. 3). The surfaces horizontally cut all the folded Quaternary units, producing flat surfaces typical of karst environments, where corrosion processes act beneath an alluvial cover (corrosion planation), controlled by the position of the water table (Fabre & Nicod 1982; Ford & Williams 2007). In Vendicari all these corrosion surfaces are inset in relation to a group of surrounding hills developed on Pliocene chalks. The slopes between different stepped corrosion surfaces show convex-concave longitudinal profiles. Lakes Pantano Grande and Pantano Piccolo are separated from the sea by calcareous ridges on which the four planation surfaces are also present.

Surface C1 develops between +15–19 m above the sea, forming a very continuous ridge in a structurally controlled NNW-SSE direction, only interrupted by the Pantano Sichilli estuarine lake. Remains of this surface can be also recognized SW of Sichilli lake and surrounding Pantano Piccolo lake, in the northern sector. This can be considered as the highest corrosion surface in the zone and also the less preserved one.

Surface C2 develops between +10−12 m above the sea, almost completely surrounding Balsamo, Piccolo and Sichilli lakes. It forms the northern and NW limits of Grande and Roveto lakes. This surface can be also recognized to the south of Cittadella as a coastal planated rim which continues some distances to the south of the studied zone.

Surface C3 develops between +3−6 m above the sea and appears discontinuosly surrounding Piccolo, Roveto and Sichilli lakes and also to the South of Cittadella.

Surface C4 develops between +1−2 m above the sea surrounding Balsamo, Piccolo and Grande lakes. It also appears in Vendicari Island (Fig. 6) and to the south of Cittadella.

The planation levels display a considerable degree of karstification, with pan-shaped dolines and extensive karren development. Most karren morphologies can be identified on the surfaces, like hohlkarren, kluftkarren, small grikes and kamenitzas, as well as ruiniform micromorphologies (Fig. 7), that were generated beneath a soil cover. Although soil is still present covering some portions of the surfaces, most of them are presently bare and hence the existing karren can be considered as mostly exhumed, a common characteristic of karst corrosion

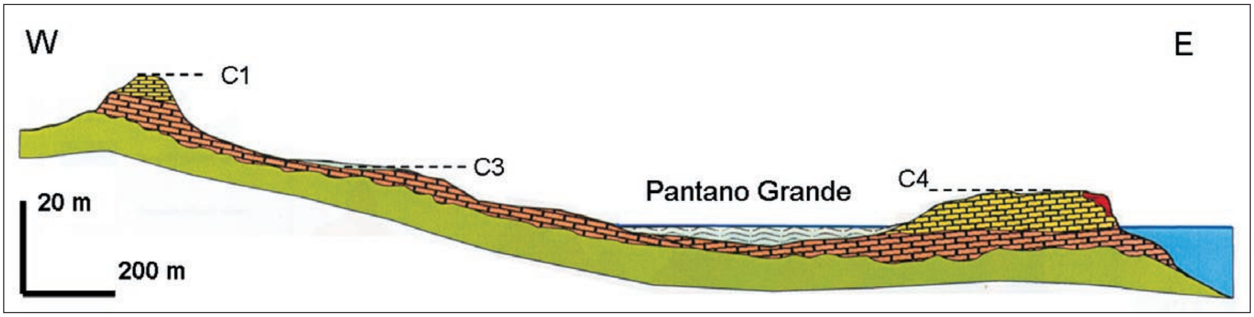

Fig. 6: Geological/Geomorphological cross section A-A' of the Vendicari lake system. See location of the cross-section A-A' and legend in Fig. 2.

Fig. 7: Exhumed karren developed upon corrosion surface C1, north of Pantano Piccolo lake.

surfaces in the Mediterranean region (Gracia *et al.* 2003). It is worth to note that these types of karren are very different from those developed on the present rocky shore platforms of the zone, represented by typical pits, small pinnacles and roughly irregular surfaces.

Kluftkarren and grikes are controlled by the fracture pattern affecting the Pleistocene carbonates. All of them are vertical open joints (up to 30 cm) filled with lateral carbonate crusts, red clays (terra rossa) and small clasts. Systematic measurement of discontinuities all along the zone shows a radial distribution with a significant concentration of joints at NNW-SSE (Fig. 8). A very minor secondary family of discontinuities appears in a normal, NE-SW direction.

Other karst forms present in the zone are dolines, usually of low depth and not well defined margins. There

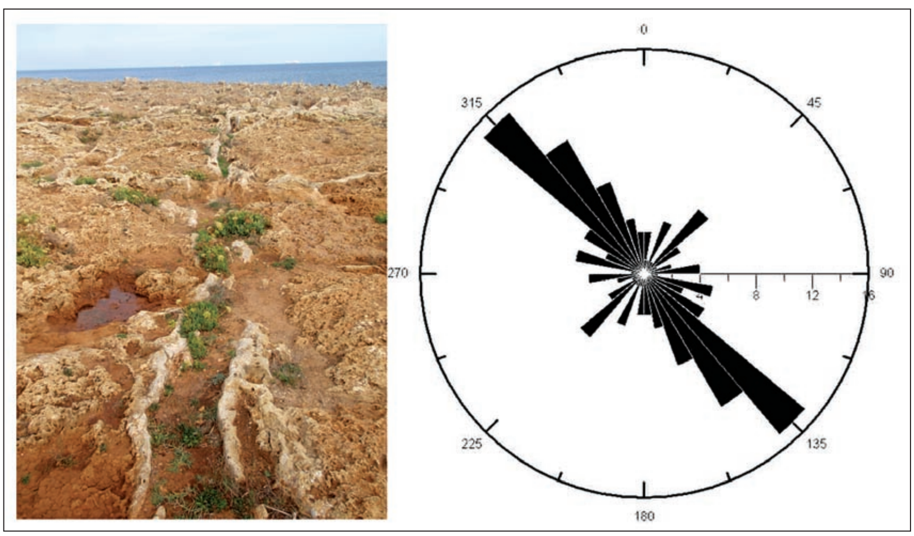

Fig. 8: Left, open vertical joint affecting Late Pleistocene carbonates and filled with calcareous crusts and terra rossa. Right, rose diagram of fractures affecting Quaternary units in Vendicari coastal zone (87 data; radial length represents percentage of data in each direction).

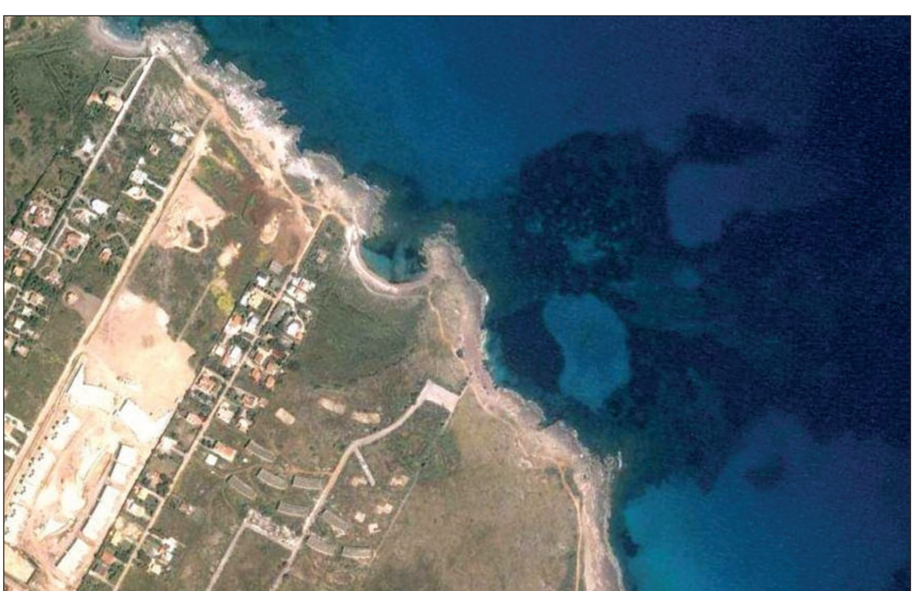

Fig. 9: Aerial photography showing several submerged dolines and a coastal captured doline to the south of Cittadella. *Photo taken in 1987, scale 1:10,600 (Società Aerofotogrammetrica Siciliana 1987).*

is a special concentration of dolines to the south of Cittadella, where coastal retreat has produced the capture of a coastal doline, which presently forms a small semicircular microbay with vertical walls. In the same sector, at least four submerged dolines can be recognized close to the shore, developed on submerged carbonates, at about 2 m depth, which could be considered as possible drowned dolines (Fig. 9). Morphological control of coastal sinkholes in the development of coastal inlets and bays has been also reported in other Italian regions (Bruno *et al.* 2008; Basso *et al.* 2013).

Available bathymetric and textural data of surface sediments from nautical charts show different rocky outcrops in the sublittoral zone and inner continental shelf together with other submerged shallow depressions covered by loose sands. The rocky outcrops form two very continuous strips NNW-SSE oriented and levelled at a broadly constant depth (Fig. 10). The first one, 1 km far from the coastline, is levelled at about 8 m depth, while the second one, 2 km far from the shoreline, develops at −14–17 m. The intervening area between the first strip and the coast, as well as that existing between both submerged outcrops, form flat-bottomed closed or semi-closed depressions, at −11 m and –25–28 m depth respectively. Out from this rocky sublittoral zone, the continental shelf shows a progressively deeper sandy bottom with no rocky outcrops.

DISCUSSION ABOUT THE EVOLUTION OF THE KARSTIC DEPRESSION

The submerged morphology of the sublittoral and inner shelf zones draws a complex closed depression with a flat bottom limited by carbonate outcrops, levelled at roughly constant depths. These characteristics are quite similar to those of karst poljes, depressions commonly developed along the Mediterranean karst regions (Gospodarič & Habič 1979; Julian & Nicod 1989; Gracia *et al*. 2002, 2003; Parise 2006). The almost closed nature of the submerged depression, its connection to a coastal area with stepped planation surfaces and the presence of other submerged closed depressions on carbonates suggest a karst origin linked to the generation and development of a polje, which at present is mostly drowned. The genesis of poljes is related to the corrosional lowering of the land surface, commonly beneath a loose, permeable and non-karst cover, usually alluvial or soil cover (crypto corrosion; Fabre & Nicod 1982). The genesis of a cryptocorrosion surface requires the exhumation of the soil-bedrock contact by erosion processes of any kind (like water erosion by runoff, glacial erosion, or marine erosion in coastal areas like in the Vendicari case). Dismantling of the soil cover may be produced by vegetation cover decrease due to climatic aridification, or to relative base level lowering and rejuvenation of the fluvial-runoff erosion, or a combination of them. The deepening of the polje bottom progresses until the topography reaches the level of frequent inundation and then the corrosion processes tend to expand the polje bottom by retreat of the marginal slopes (Ford & Williams 2007). The sequence of four-stepped levels of corrosion surfaces represents alternating periods, some of them dominated by deepening and others by planation and expansion of the polje bottom, always controlled by the position of the water table. In coastal environments poljes can develop seasonal or permanent lakes, according to sea level (Bonacci 1987; Nicod 2003).

The N-S succession of interconnected closed depressions excavated on carbonates could be interpreted as an uvala. In reality it is not easy to differentiate uvalas and poljes. Cvijić (1893) considered that uvalas were genetically an intermediate stage between dolines and poljes and concluded that it is difficult to clearly differ between uvalas and poljes. In the description and classification of poljes made by Gams (1978) intermediate terms can be found, like uvala-like-polje, polygenetic polje or compound polje. Nicod (2003) indicates that some poljes may proceed from connection of previous uvalas. Diagnostic indicators of poljes with respect to uvalas are: flat bottom (uvalas usually have uneven bottom), karst inflow and outflow, terraced corrosion levels, steep slopes surrounding the bottom, tectonic origin or control and relationship with water table, among others. A discussion about this topic can be found in Frelih (2003). An additional diagnostic indicator in favour of the polje hypothesis is the recognition of cryptocorrosion markers, since cryptocorrosion is a genetic process typical of poljes (Fabre & Nicod 1982; Nicod 2003): hohlkarren, kluftkarren, etc., are very different from the typical coastal phytokarst micromorphologies (Ford & Williams 2007). The absence of these cryptokarren morphologies does not discard the polje hypothesis, but their presence is an argument in favour of the latter. These morphologies are present in all the surfaces surrounding Vendicari lakes, and the depressions also fulfill all the other requirements to be considered as a polje.

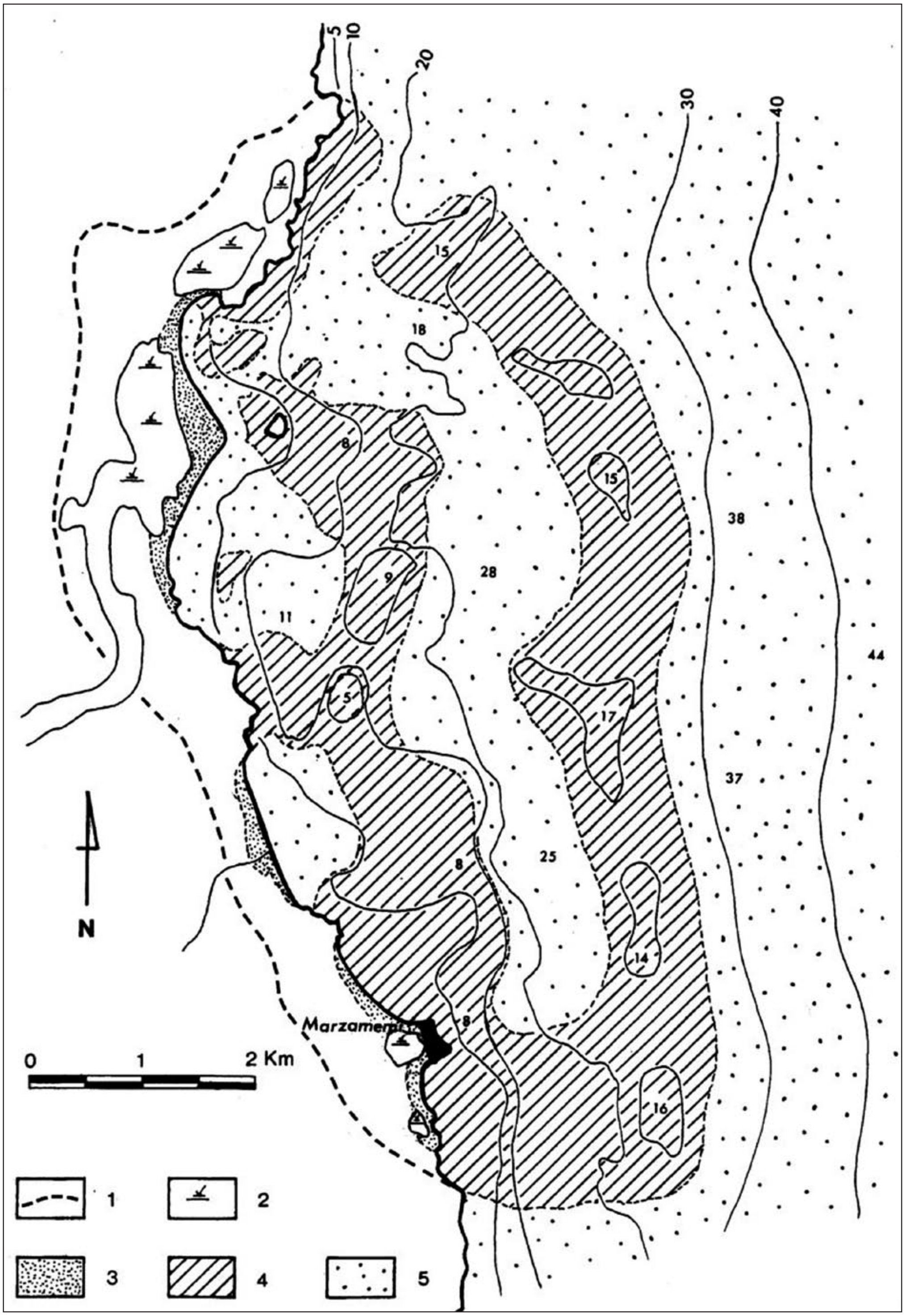

Fig. 10: Bathymetric and morphological map of the submerged bottoms in the vicinity of Vendicari coast, elaborated from data included in the Italian nautic chart no. 21, at 1:100,000 scale (Istituto Idrografico della Marina 1999). 1-emerged limit of the corrosion surfaces; 2-wetlands; 3-beaches; 4-rocky outcrops of submerged carbonates; 5-submerged sand sheets. Numbers refer to meters below sea level.

The enveloping line enclosing the corrosion surfaces and the submerged depression draws an approximate figure of the original karst depression, which could have reached about 6 km long in a N-S direction, and width of over 5 km (Fig. 10). Height difference between the highest emerged corrosion surface and the deepest submerged bottom is slightly higher than 40 m. These dimensions are relatively modest if compared with other typical Mediterranean poljes (Gracia *et al.* 1996; Gams 2005). Some poljes identified in the Venetian Prealps are smaller (usually less than 5 km long) and typically deep, with more than 200 m of vertical difference between the surrounding summits and the polje bottoms (Lehman 1959). Instead, the Canale di Pirro polje, in Apulia (SE Italy) is located on a wide planated zone and has an overall length of some 30 km (Parise 2006). Several poljes have been identified in the North and NW zones of Sicily (Trapani, Palermo and Madonie mountains), all of them exhibiting dimensions lesser than 8 km^2 and controlled by faults (Di Maggio *et al.* 2012).

Although drowned karst features are widely cited in the literature (Paskoff & Sanlaville 1978; Ford & Williams 2007) and some coastal poljes have been referred in the Mediterranean context (Peña-Monné *et al.* 2008), not many examples exist regarding submerged poljes. Gavazzi (1904) describes in Croatia the coastal freshwater lakes of Vransko Jezero (South East of Zadar) and Vransko Jezero (Cres Island) as polje floors, deepened when sea level was lower and transformed into lakes when sea level raised their bottoms. Some deep submarine depressions south of Florida have been interpreted as karst features (Jordan 1954). Jennings (1985) describes large karst depressions beneath the sea in Šibenik harbour (Croatia) and the Bay of Kotor (Montenegro), while the Novigrad Bay (Istria, Croatia) is regarded by this author as a polje invaded by the sea. Other examples of coastal or drowned karstic depressions are cited by Gams (2005) in the Dalmatian coast, or by Taviani *et al.* (2012) in the Italian Adriatic coast and continental shelf. It is very likely that in karst coasts where many originally subaerial morphologies (dolines, caves) are at present submerged in the sublittoral zone due to sea level rise, poljes can also be found below present sea level. The scarcity of previous cites referring drowned poljes probably is due to their shape and dimensions (wide, flat depressions) and their natural tendency to be filled with marine sediments, which would obliterate their original aspect. Only in the case of poljes recently drowned by the last eustatic cycle and located in coasts with little sediment supplies they would still maintain at present great part of their original morphology below sea level. This seems to be the case of Vendicari, where the subhorizontal disposition of the carbonate series surely favoured the development of a wide depression with low depth.

Many poljes have a tectonic origin or at least a strong structural control (Gams 1978; Julian & Nicod 1989; Gracia *et al.* 2003; Di Maggio 2012). The longitudinal development of these depressions following active or neotectonic faults is a common indicator of this relationship. Eastern Sicily is considered as a region submitted to tectonic movements during the Late Pleistocene. Antonioli *et al.* (2006) concluded that the Hyblean Plateau is experiencing a mean uplift rate of 85 mm/ka, according to the elevations of MIS 5.5 deposits, probably because of the effects of the near offshore Malta Escarpment, a NNW-SSE active fault of regional importance. Open joints measured in Vendicari indicate that prevailing directions of fracturing are parallel to the Malta Fault, which would confirm the hypothesis of Antonioli *et al.* (2006). The slight rate of uplift would also be justified by the radial distribution of minor fractures and joints (Fig. 8). Furthermore, the general outline of the Vendicari submerged polje presents a clear control of the NNW-SSE structural trend, which also conditions the orientation of the Marzamemi rocky coast, south of Vendicari (Fig. 10). Hence, it could be assumed that a slight uplift during the Late Pleistocene, especially supported by Malta Fault-parallel fractures, would have been the responsible for the primary generation of a gentle tectonic depression NNW-SSE oriented. As a consequence, the high density of open fractures would have enhanced karst dissolution, which led to the initiation of corrosion planation processes and subsequently to the formation of a polje.

In contrast with continental poljes, where the stepping of corrosion surfaces is typically linked to falling episodes in the karst base level, in Vendicari the hydrological base level is represented by the sea level. In Vendicari coastal area, carbonate-rock aquifers have been probably karstified during the Late Pleistocene sea-level lowstand.

The subaerial corrosion surfaces at Vendicari are indicative of the height reached by the relative sea level in different moments along the Late Quaternary. In this sense, the regional highest altitude reached by the Thyrrenian marine terraces is + 15 m above the sea (Antonioli *et al.* 2006). Small sea level oscillations around that level as well as the later sea level fall during the last glaciation should have brought about the stepping of karst surfaces and the subsequent compartmentalisation and splitting of the original depression into other minor ones – the present Grande, Piccolo and Balsamo lakes, and maybe the depression encompassing Roveto and Sichilli lakes. The topographic lowering associated with the polje bottom deepening would have also favoured the incision of the Saia Scirbia river (Figs. 1 and 3), which probably continued to the NNE crossing the northern margin of the polje (Fig. 10). Subsequently, postglacial sea level/base level rise produced sedimentary deposition in the lakes, as well as the transformation of the lower Saia Scirbia river valley into a progressively infilling estuary. The estuary was closed by the post-glacial growth of a confining sand barrier, where a cuspate sandy foreland formed in the Punta d'Isola has intermittently functioned as a tombolo in historical times.

CONCLUSIONS

The formation, variability and configuration of Vendicari coastal lakes are strongly influenced by inherited geological factors at long-term temporal scale like relative sea-level fluctuations, regional tectonic setting and mainly karst processes. This is an unusual case of coastal lakes produced by karst processes, especially if we consider the broad context where the lakes were generated: a probable Late Pleistocene polje presently drowned in the inner shelf, still recognizable through nautical charts. Its development and the generation of up to four stepped corrosion surfaces give an idea about the velocity at which poljes and other similar karst depressions can be formed under favourable conditions like those converging in coastal environments: enhanced carbonate dissolution and rapid base level (e.g. sea level) fluctuations. Slow to moderate tectonic uplifting during the Late Pleistocene very probably favoured the stepping of the surfaces, by progressive water table lowering. Prevailing orientation of joints, as well as of the drowned polje itself, suggest that regional stress field, controlled by the Malta Fault, were the responsible for the genesis of the depression, which subsequently evolved by karst corrosion processes during the last sea level lowstand.

Theoretically submerged poljes may present a very low preservation potential, linked to their tendency to be filled with marine sediments in the medium-long term. Only poljes recently drowned during the last eustatic cycle and located in coasts with little sediment supplies would still maintain at present great part of their original morphology below sea level. This seems to be the case of Vendicari, which gives it an additional interest.

Once the polje was drowned after the last sea level rise, during Holocene and recent times the sea level stabilization on a height roughly similar to the present one favoured the prevalence of coastal transport and deposition processes. As a consequence, a beach barrier developed closing the pre-existing karst-originated coastal embayment.

ACKNOWLEDGEMENTS

The authors are very grateful to the Ispettorato Ripartimentale delle Foreste di Siracusa, Administrator of Vendicari Natural Reserve, for logistic field support. This work is a contribution to Research Group RNM-328 of the Plan Andaluz de Investigación.

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