Morphometric Comparison of Dolines in Three Karst Landscapes Developed on Different Lithologies

E. Pardo-Igúzquiza, J. M. Gil-Márquez, M. Mudarra, B. Andreo, and J. J. Durán-Valsero

Abstract

The present contribution compares the geomorphological characteristics of dolines developed in three different geological contexts in southern Spain: an evaporite tectonic melánge, a bare-carbonate massif, and an outcrop of inter-stratified sedimentary gypsum sequence. In the three cases, the closed depressions have been identified and mapped using digital elevation models with a spatial resolution of 5 m, and the results were validated in the field. To reveal similitudes and differences due to distinctive geological and climatological settings between the three sites, morphometric and spatial analyses were applied to the threes sites: size-distributions, relationships between area and depth, preferential directions, and point field analysis, among others. The results show apparent differences between the carbonate and the two evaporitic settings. Carbonate outcrop displays larger dolines, implying a lower doline density, while the density of depressions rises in the evaporite sites. The results also show a dominant ENE-WSW alignment of dolines in two areas, in agreement with the main fault families of the Betic Cordillera, which evidences the tectonic influence on the karst development. However, in the gypsum karst, other directions appear related to the surficial drainage network connected to dolines. Finally, in the tectonic melange, the uneven distribution of lithologies affects karstification distribution. Geological differences (both lithology and structure) imply changes in solubility and karstification dynamics that, together with other factors such as the climatic conditions and the exposure time, affect the genesis of the depression and, ultimately, its size and shape. All that combined explains the differences in morphometric parameters and spatial.

Keywords

Karst • Morphometric analysis • Digital elevation models • Sinkholes

1 Introduction

Dolines are the most typical landform of the karst landscape on the metric scale (Sauro 2003). In karst terrains, most dolines have been formed by the solution of the bedrock (limestone, dolostone, gypsum, and halite), although some dolines form by terrain subsidence or collapse (Ford and Williams 2007), which ultimately are also related to the solution of the bedrock. Dolines have been intensively studied since the times of Cvijić (White 1988) and the first karst geomorphologists. Doline mapping has been an important task in karst geomorphology, not only by its scientific interest but also by its importance in sinkhole hazards (Gutiérrez et al. 2008), preferential recharge in hydrogeology (Somaratne 2014), land use management (Hughes et al. 1994), and biodiversity studies (Bátori et al. 2019). Bondesan et al. (1992) recognized that measuring morphometric parameters through field surveys or over maps and aerial photographs requires hard work and is time-consuming. However, they also pointed out that the morphometric analysis has been facilitated by the availability of computers and the incipient, at the time, geographical information

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B. Andreo et al. (eds.), *EuroKarst 2022, Málaga*, Advances in Karst Science,
https://doi.org/10.1007/978-3-031-16879-6_32

systems. Also, they highlighted that the altimetric parameters of dolines had been very often neglected while the analysis has focused on planimetric attributes.

In the last few decades, the availability of digital elevation models (DEMs) has improved quantitative terrain analysis in general and the morphometric analysis of dolines in particular (Lyew-Ayee et al. 2007). Based on the availability of high-resolution DEMs, Pardo-Igúzquiza et al. (2013) propose for the automatic detection and delineation of depressions a simple idea: a digital map of depressions can be easily obtained by the map algebra operation of subtracting the depression-free DEM from the original DEM. The DEM can be combined with satellite images and morphometric analysis to discriminate different types of depressions. Improvements in the acquisition of lidar data and the use of crewless aerial vehicles have improved the spatial resolution of the DEMs, and there is an increase in the detail that can be observed of individual dolines in order to extend their morphometric analysis. All the previous references are morphometric and spatial analyses of dolines ensembles in carbonate karst systems. Fewer studies have been done on morphometric analysis of karst depressions in other types of karst systems, which is related to their smaller world abundance. Nevertheless, morphometric analysis of gypsum karst is not rare (Keskin and Yilmaz 2016).

This contribution analyses the geomorphological characteristics of dolines developed in three different geological contexts in Southern Spain: an evaporite tectonic mélange, a bare-carbonate massif, and an outcrop of inter-stratified sedimentary gypsum sequence. The method described by Pardo-Igúzquiza et al. (2013) has been used for the identification and delineation of the closed depressions, and the results are shown and discussed next. By comparing the geomorphological difference between them, this work aims to advance in understanding their genesis and assess the role of different factors, including geological ones, on the evolution of depression landforms in karst.

2 Study Area

The location of the three different karst areas selected in southern Spain is shown in Fig. 1. The carbonate karst is the Sierra Gorda karst massif (SG), a medium relief karst (with maximum altitudes lower than 1700 m a.s.l.) with a NW–SE oriented elliptic shape that is developed on Jurassic limestones and dolostones (López-Chicano 1992). The karst in an evaporitic mélange is part of the so-called "Trías de Antequera" (Sanz de Galdeano et al. 2008), a Triassic tectonic mélange and olistostrome with diapiric structure that encloses blocks of gypsum and halite (among other lithologies) embedded in a fine-grained matrix of clays and marls. The gypsum karst of Sorbas is formed by 60-m thick Neogen gypsum deposits related to the Messinian Salinity Crisis event (Braga et al. 2006).

Figure 2 shows the digital elevation models (DEMs) of the three karst systems. The three DEMs have a spatial resolution of 5 m and are freely available from the Internet site of the Instituto Geográfico Nacional (www.ign.es). The southern limit of the Sierra Gorda DEM has been arbitrarily chosen in order to exclude the Zafarraya polje, a huge karst depression that can be considered as an exception if compared with a typical doline of the highest part of the Sierra Gorda karst system. The area of each of the three karst systems considered is 267, 69, and 31 km^2 for the Sierra Gorda carbonate karst, Meliones evaporitic mélange karst, and Sorbas gypsum karst, respectively (Table 1). The method described by Pardo-Igúzquiza et al. (2013) has been used for the identification and delineation of the closed depressions, and the results are shown and discussed next.

3 Results

The maps of karst depressions are shown in Fig. 3a–c. Results were validated in the field. In the Sorbas gypsum karst, three large depressions corresponding with gypsum quarries were filtered out from the map. It may be seen how the maximum depth of a depression from its rim is −38.44 m in SG, then −18.08 m in ME and −14.16 m in the SO (Fig. 3). Dolines in the Sierra Gorda carbonate karst appear in a doline field with the individual dolines smoothly rounded and aligned, most likely along fractures. The dolines in the Meliones evaporitic mélange karst seem more asymmetrical with an almost triangular outline. On the other hand, the dolines in the Sorbas gypsum karst are the most

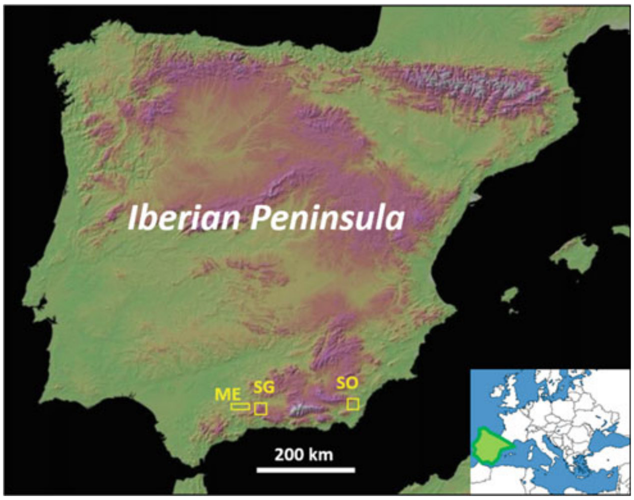

Fig. 1 Geographical location of the three karst systems in Southern Spain. SG: Sierra Gorda carbonate karst; ME: Meliones evaporitic mélange karst; SO: Sorbas gypsum karst

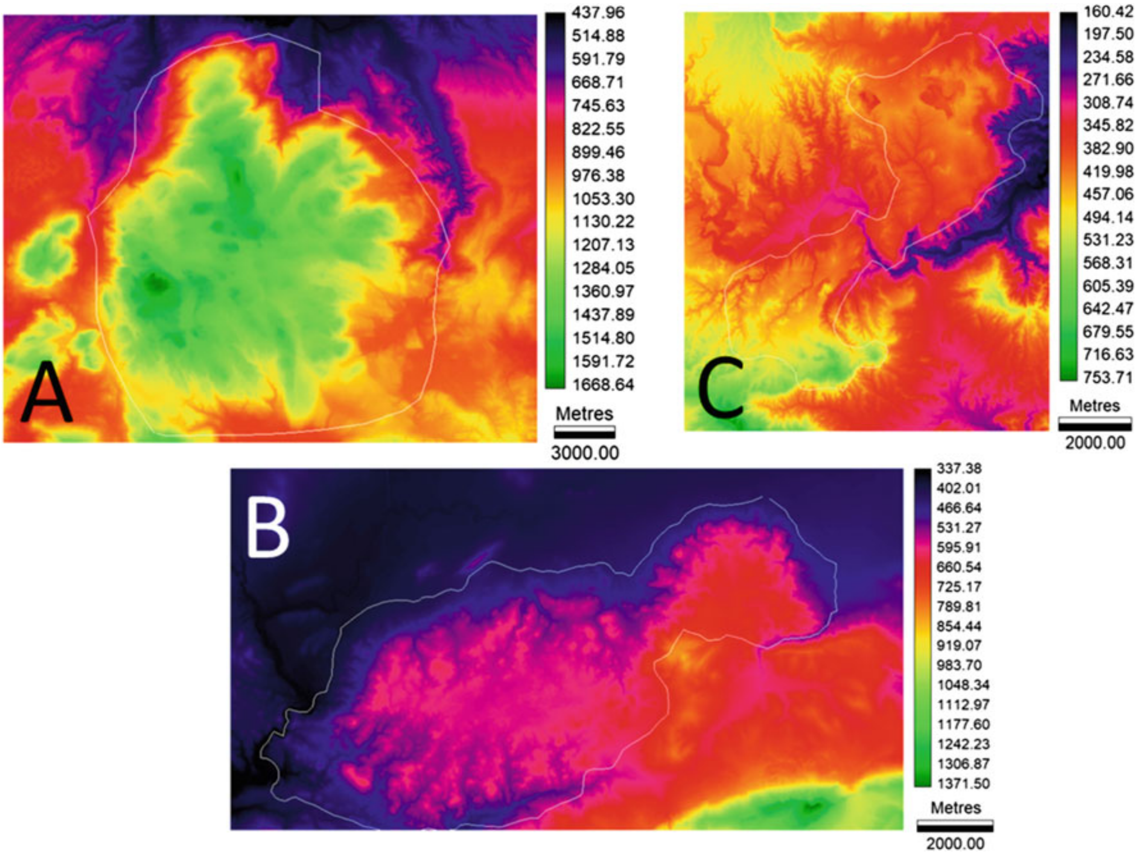

Fig. 2 Digital elevation models (DEMs) of the three karst systems in Southern Spain. A: Sierra Gorda carbonate karst; B: Meliones, evaporitic mélange; C: Sorbas gypsum karst. The colour legend is the altitude in metres above the mean sea level. The spatial resolution of each DEM is 5 m. The white lines represent the borders of the karst systems

Table 1 Surface of the study areas (first column) and statistics of the morphometric characteristics of dolines. N: number of dolines. D: density of dolines in dolines per km^2. 1 N: number of one-cell dolines (dolines < 25 m^2). N > 250: number of dolines larger than 250 m^2. D: Median of the diameter assuming the shape of the doline is a circle with the same area. D/R: the ratio diameter/depth

	Area (Km^2)	N	D Density N/Area	1 N	N > 250 m^2	Mean area (m^2)	Median area (m^2)	Median depth R (m)	Median equivalent diameter D (m)	Ratio D/R
Sierra	267	3100	12	370	1931	1510	400	0.7	22	31:1
Gorda				29%	62%					
Meliones	69	1273	18	370	267	885	75	0.36	10	28:1
				29%	21%					
Sorbas	31	1145	37	366	161	309	75	0.31	10	32:1
				32%	14%					

asymmetrical and seem to have been developed along a gully. The identified closed depressions have been 3100, 1273, and 1145 for the SG carbonate karst, ME mélange karst, and SO gypsum karst, respectively (Table 1). Thus, considering that the surface of the analysed outcrops is 267 km^2, 69 km^2, and 31 km^2 for SG, ME, and SO, respectively, their mean density of kart depressions per km^2 is 12, 18, and 37. However, the mean size of the depression progresses in the reverse order, and is 1510 m^2 (SG), 885 m^2 (ME), and 309 m^2 (SO). Other statistics of the number and area of the dolines are shown in Table 1.

Figure 4 shows the histograms of the areas of the karst dolines in the three study areas. It may be seen how the depressions developed in evaporitic systems (gypsum and the evaporitic mélange) have a similar size distribution, which is markedly different from the distribution of doline size in the carbonate karst. The evaporitic karsts have a more significant proportion of small depressions.

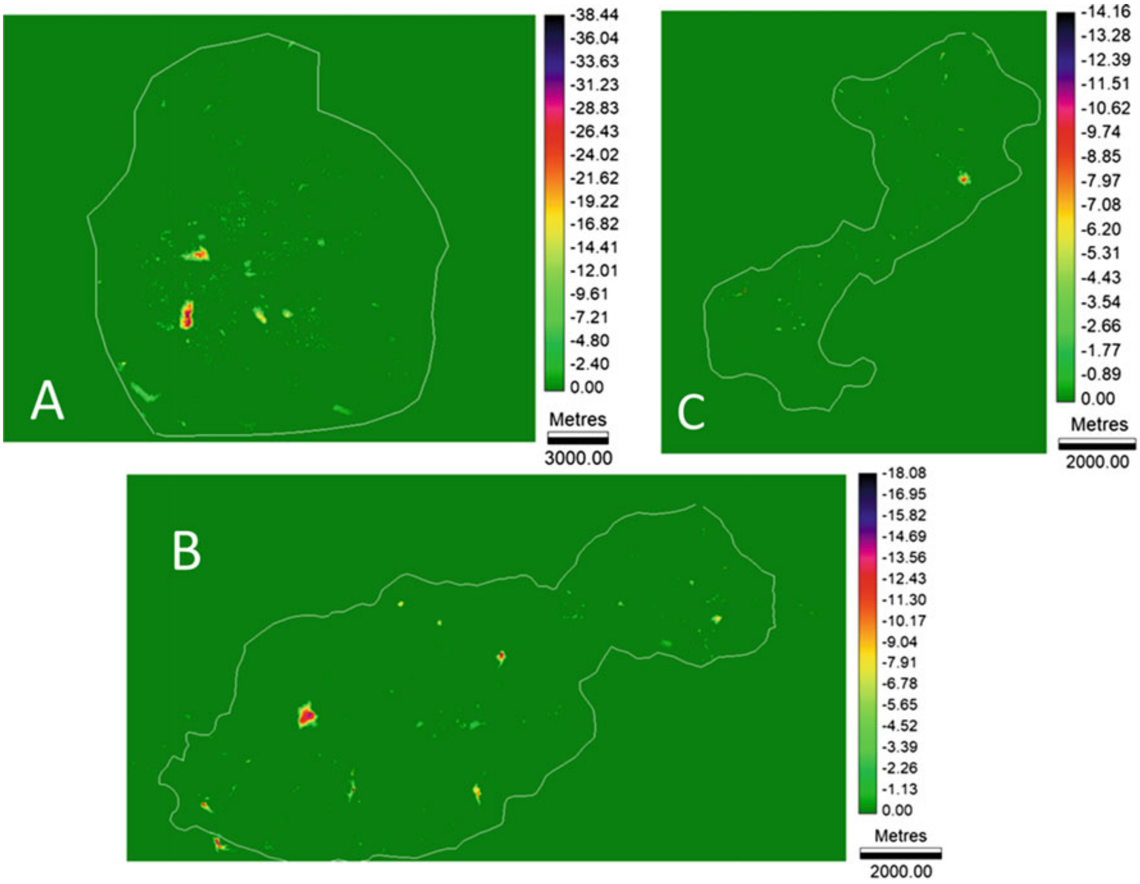

Fig. 3 Maps of identified and delineated karst depressions in A: Sierra Gorda carbonate karst (SG); B: Meliones evaporitic mélange (ME); C: Sorbas gypsum karst (SO). The colour legend bar is the depth of each doline from its lowest edge in metres

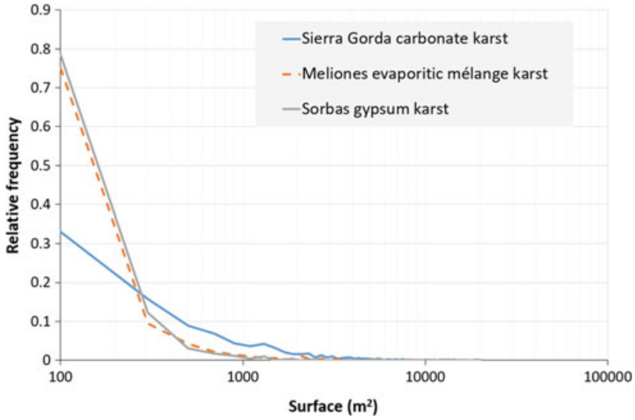

Fig. 4 Histogram (relative frequencies) for the area of the karst depressions in the three study sites

Figure 5 shows the relationships between the maximum depth of the dolines and their area. In all the cases, there is a positive correlation between both parameters. A power law has been fitted to all the scatterplots (Fig. 5a–c), with exponent values of 0.62 (SG), 0.51 (ME), and 0.64 (SO). Thus, there is a clear similarity between the carbonate outcrop (SG) and the gypsum karst systems (SO), which differ from the evaporitic melange system (ME). Thus, dolines of the same surface developed in carbonates and gypsum outcrops will have a higher maximum and mean depth than if formed in evaporitic melange. More frequent collapse processes may explain that in the later karst system.

Figure 6 shows the power law fitted to the log–log plots of the size distribution of depressions for the SG, ME, and SO karst systems, respectively. The exponent of the power law can be considered the fractal dimension of the size distribution and has values of −1.04 (SG), −0.833 (ME), and −0.627 (SO). The fitting of straight lines to the log–log plot is qualitative proof of the fractal character of the sizes of dolines in karst systems independently of their lithology.

When each doline is substituted by its centroid, the fields of points shown in Fig. 7a–c are obtained for the SG, ME, and SO karst systems, respectively. It may be seen how the points in the SG carbonate karst cluster in given areas around the centre of the karst massif, while for the evaporitic karst systems (ME and SO), the dolines appear more isolated or concentrated in linear clusters along with drainage

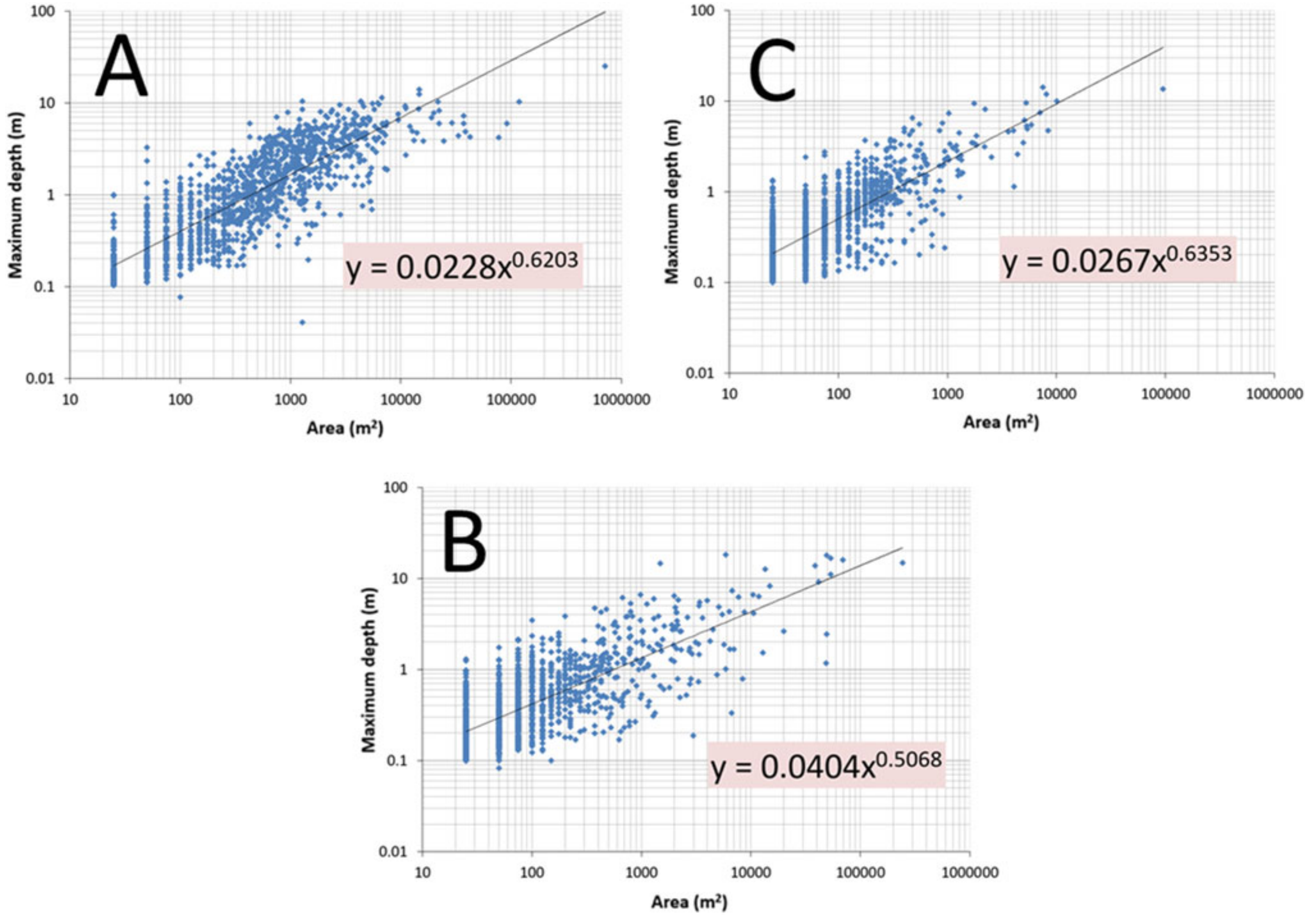

Fig. 5 Relationship between the maximum depth of each depression and its area. A: Sierra Gorda carbonate karst; B: Meliones evaporitic mélange; C: Sorbas gypsum karst

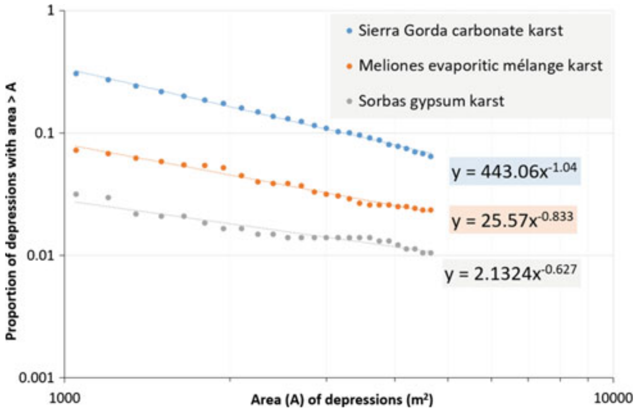

Fig. 6 Power law fitted to the size distribution of dolines in a log–log plot for in Sierra Gorda (A), Meliones (B) and Sorbas (C)

patterns. Nevertheless, the SO system has larger clusters than the ME system. This can be reflected in the fractal dimension of the spatial distribution of points shown in Fig. 8, which has a higher value for the SO system: 1.14, 1.06, and 1.40 for the SG, ME, and SO karst systems, respectively.

Figure 9a–c shows the rose diagram (or angular histogram) of the main directions of the alignments of points in Fig. 7a–c for the SG, ME, and SO karst systems, respectively. The main modes are for azimuths N70E and N150E for the SG system, N65E for the ME system, and N35E for the SO system.

4 Discussion

Dolines in a carbonate karst area have a slow evolution so that the landscape looks invariable from year to year. This is because of the relatively low solubility of carbonates and their high mechanical strength. In general, the probability of occurrence of a new doline, from year to year, in carbonate karst is small, and thus, there is little risk of subsidence or collapse. In gypsum karst terrains with a thick geological formation of massive gypsum, the behaviour may be similar although the rock is more soluble. On the other hand, in a

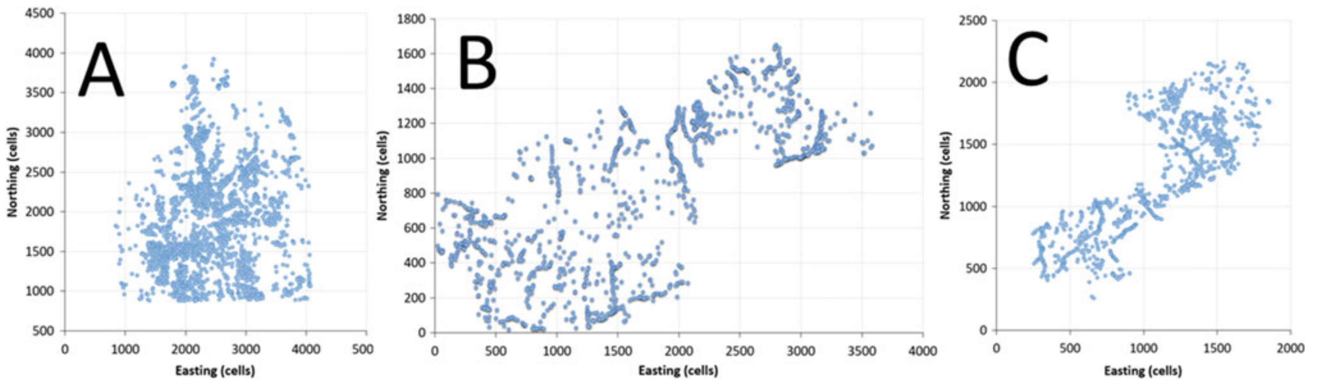

Fig. 7 Location of centroid points of doline in Sierra Gorda (SG), Meliones (ME), and Sorbas (SO)

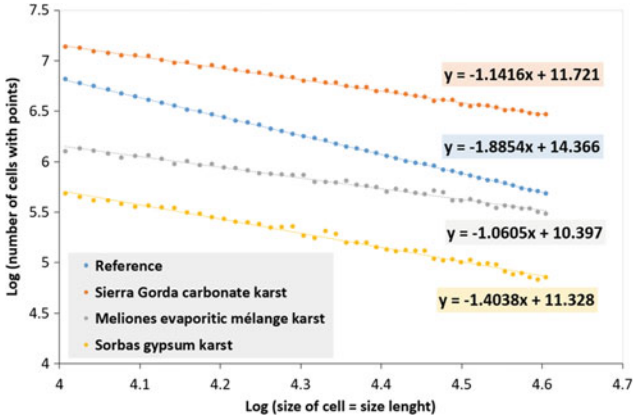

Fig. 8 Box counting fractal dimension of point fields of karst depressions for Sierra Gorda (A), Meliones (B), and Sorbas (C)

mélange with gypsum blocks, the karst evolution is more dynamic because there is more concentration of flow crossing the marl and clay landscape and focusing towards the dolines developed in the gypsum blocks. Thus, in the karst developed in an evaporitic málange, the high dynamical development of karst depressions and their changes are perceptible at the human scale with noticeable changes from year to year. That has been detected in the field trips to the Meliones system. The histogram of the surface of closed depressions in Fig. 4 clearly shows the similarity of the two evaporitic rock systems (ME and SO) and their difference from the carbonate system (SG). The greater proportion of large dolines in the latter could be related to the older age of the outcrop and the more wet conditions, which would have favoured further development of depression. The clear asymmetry of the doline in the SO gypsum karst is because of their relationship with the surface drainage network. This is confirmed by the alignment of such zones along with gullies that differ from Sierra Gorda (SG) and Meliones (ME), where the dolines align along with the main fault families in the Betic Cordillera that is ENE-WSW (Fig. 9).

A distribution of points that will tend to fill the space will have a fractal dimension close to 2. The higher value of the fractal dimension of the SO system implies that the field of points in Fig. 7c tends to fill the plane more uniformly than the SG and ME karst systems. From a morphodynamic point

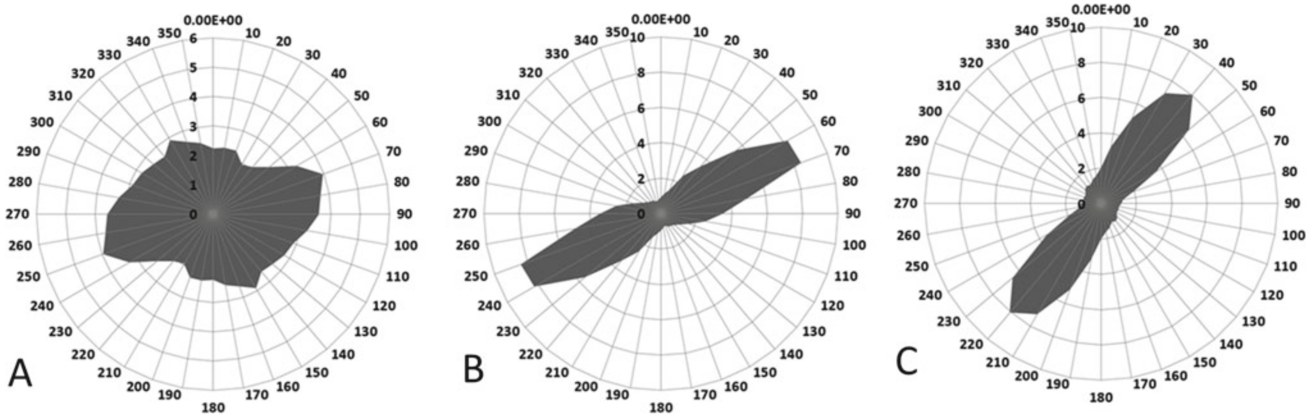

Fig. 9 Rose diagram (or angular histogram) of the main directions of the alignments of centroid points of dolines in Sierra Gorda (A), Meliones (B) and Sorbas (C)

of view, dolines constitute elementary hydrographic units (Bondesan et al. 1992), which with their systems of slopes, covey water to a central point where recharge occurs (Ford and Williams 2007). Thus, where the bedrock is more soluble, and the outcrops are extensive, the distribution of dolines would be more uniform and they would be more abundant. That explains the differences between the gypsum system (SO) and the mélange systems (ME), where the gypsum outcrops are patched.

5 Conclusions

Morphometric and spatial analysis provides a mean for studying the differences between karst landscapes. In this study, the results of the morphometric and spatial analysis of karst closed depressions (dolines) developed in a carbonate, an evaporitic mélange, and a gypsum karst system have been compared. The geologic differences are clear, but the purpose has been to reveal intrinsic differences between the karst depressions in relation to their lithology and its implication in the karst surface dynamics. It is obvious that even between three different carbonate karst, there will be differences because there are many factors affecting the development of dolines, but in this study, in addition to those factors, there is the fact of the differences between landscapes being developed on carbonates, gypsum, and an evaporitic mélange. The comparison between such three different karst landscapes is also a novel aspect of this work. The differences in rock solubility, lithology, and structure of the outcrops, which imply different karst dynamics, explain the differences between the morphometric parameters of the three karst systems. However, other factors such as the climatic conditions and the exposure time cannot be neglected.

Acknowledgements The present work was supported by research projects PID2019-106435GB-I00 of the Ministerio de Ciencia e Innovación of Spain and PI20-01118 of the Junta de Andalucía

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