Geomorphology of Mediterranean submarine canyons in a global context – Results from a multivariate analysis of canyon geomorphic statistics

Peter T. Harris and Miles Macmillan-Lawler

GRID-Arendal, Norway

ABSTRACT

Submarine canyons in the Mediterranean and Black Seas stand out as globally different based on studies of global canyon geomorphology; they are more closely spaced, more dendritic (more limbs per unit area), shorter, have the smallest mean area, are among the most steep and have a smaller depth range than canyons that occur in other regions of the world. Here we present the results of a multivariate analysis of submarine canyon geomorphology to explore in more detail the apparently unique attributes of Mediterranean canyons. We find that Mediterranean canyons can be divided into six Classes, dominated by "Class 4" that is characterized by small area, close canyon spacing and a relatively high percentage of shelf incising canyons. On a global basis, Class 4 canyons are found to occur mainly (68%) on active continental margins. Examples of other regions in the world containing large numbers of Class 4 canyons are described.

1. INTRODUCTION

Submarine canyons in the Mediterranean and Black Seas stand out as globally different based on studies of global canyon geomorphology (Harris and Whiteway, 2011; Harris *et al.*, 2014a). Mediterranean canyons are more closely spaced, more dendritic (more limbs per unit area), shorter, have the smallest mean area, are among the most steep and have a smaller depth range than canyons that occur in other regions of the world. The question arises: "What physical processes explain these observed geomorphic attributes that are unique to Mediterranean canyons?"

The explanation for these differences is not simply due to a difference in data quality for the Mediterranean compared with other areas. The bathymetric models used by Harris and Whiteway (2009) and by Harris *et al.* (2014a) used versions of the Smith and Sandwell (1997) satellite altimetry dataset. The SRTM PLUS 30 v7 arc second model (Becker *et al.*, 2009) incorporated data from the Mediterranean margin of the highest quality (based on multibeam sonar data; Amante and Eakins, 2009; Becker *et al.*, 2009). But this factor does not explain the differences in observed geomorphology. Take canyon spacing, for example; some locations exhibiting close canyon spacing, such as the South Pacific, are not based on exceptionally high-quality data (Harris and Whiteway, 2011). Furthermore, locations having excellent data quality do not necessarily exhibit closely-spaced canyons, such as the margins of Japan and of the United States. Inspection of the global database for canyon length, slope, area and depth range confirms the view that the observed differences cannot be explained by data quality alone.

Other factors that might explain the geomorphic attributes unique to Mediterranean canyons include global sea level changes and density currents (Harris and Whiteway, 2011; Harris *et al.*, 2014a). Sea level lowering and desiccation of the Mediterranean basin that occurred during the late Miocene "Messinian Salinity Crisis" (e.g. Lofi *et al.*, 2005; CIESM, 2007) may have played a role in regional canyon development. The subaerial exposure and erosion of the continental margins bordering the Mediterranean are well documented in the literature (Hsü *et al.*, 1978; Druckman *et al.*, 1995; Rouchy and Caruso, 2006) and this phase of subaerial erosion is a unique feature of that region's geological history. The incision of the margin by rivers during this period would have created incipient canyons that were further developed by submarine processes following re-filling of the Mediterranean basin. However, tectonic uplift and margin progradation will have significantly modified or masked many canyons formed during the late Miocene, particularly along the northern active margin of the Mediterranean (e.g. Bertoni and Cartwright, 2005; Ridente *et al.*, 2007). A large percentage of shelf-incising canyons might be expected if subaerial erosion had played a major role in canyon development, and yet the Mediterranean does not in fact have a large percentage of shelf-incising canyons compared with other regions of the world (Harris and Whiteway, 2009).

Another possibility is the role played by erosive density currents formed in winter by cooling of shelf water masses, which cascade down submarine canyons. In the Gulf of Lion, down-canyon current speeds of up to 85 cm s^{-1} have been measured at 5m above bottom in 750 m water depth associated with winter cooling events (Canals *et al.*, 2006). Similar oceanographic processes have been invoked by Mitchell *et al.* (2007) to explain the headward erosion of Bass Canyon located in southeastern Australia during the Pleistocene. But it is not clear how this process alone could explain the geomorphic differences observed.

In order to explore possible reasons behind the geomorphic differences between the Mediterranean and other canyons in the world ocean, a new global database of submarine canyons (Harris *et al.*, 2014a) is here analysed using multivariate statistical methods. The new geomorphic data are based on interpretation of the Shuttle Radar Topography Mapping (SRTM30_PLUS) 30-arc second database (Becker *et al.*, 2009) as modified by Harris *et al.* (2014a) to include better quality data in the region around Australia. "Large" canyons were mapped in this study based on the definition of Harris and Whiteway (2011), which requires canyons to extend over a depth range of at least 1,000 m and to be incised at least 100 m into the slope at some point along their thalweg. Differences in canyon morphology highlighted by the results of multivariate analysis will be presented and discussed with the aim of seeking further possible explanations for the unique geomorphic attributes exhibited by Mediterranean canyons.

2. Methods - Multivariate analysis of canyons

A total of 9,477 submarine canyons are included in the global database compiled by Harris *et al.* (2014a) which also provides the compiled geomorphic attributes for each canyon, used here as input variables for a multivariate analysis. The input variables used are length, width, mean canyon depth, canyon depth range (delta depth), canyon spacing and the frequency of occurrence of shelf-incising canyons. Detailed descriptions of these variables are as follows:

Length: the maximum length of the canyon as calculated using a bounding box.

Width: the maximum width of the canyon as calculated using a bounding box.

Mean depth: the mean depth of the canyon polygon.

Delta Depth: the difference between the minimum depth and maximum depth within the canyon.

Spacing: the distance between adjacent canyons measured as the distance to the nearest canyon.

Frequency of occurrence of shelf-incising canyons: this is a measure of the area of shelf incising canyons divided by the total area of canyons that occurs within a given area, expressed as a percentage. The number was calculated as the percent of area of shelf incising canyon polygons occurring within a search radius of 500 cells.

The variables for each canyon were calculated in ArcGIS based on the geometry of the canyons and analysis of the modified SRTM30_PLUS bathymetric model. Each of the six variables was rasterised to a standard 0.5 minute grid (consistent with the modified SRTM30_PLUS bathymetric model). Each variable was scaled so that its range was between 0 and 100 to ensure equal weighting in the classification process using a linear transformation. The classification used the Iso cluster unsupervised classification algorithm in ArcGIS, run for between 3 and 20 classes.

3. RESULTS

There are 817 canyons in the Mediterranean and Black Seas (refereed to here as simply the Mediterranean), which is the focus of the analysis presented here. The first step in our analysis was to calculate the discrete clusters for different canyon classes calculated for the global database of 9,477 canyons and then examine the numbers of canyons in each cluster occurring in the Mediterranean. The number of canyons from 3 to 20 clusters that occur in the Mediterranean (shown in Table 1) illustrates that with 6 clusters there are 4 significantly large populations in the Mediterranean (i.e. having more than 20 members; Classes 1, 3, 4 and 5). Adding additional clusters does not result in the creation of a greater number of significantly large clusters. Hence, six clusters was the number used in the present study to assess canyon populations.

Table 1. Number of canyons from the Mediterranean according to Class for differing numbers of clusters calculated for the global canyon database. With six clusters there are four significantly large populations in the Mediterranean (i.e. having more than 20 members; Classes 1, 3, 4 and 5). Adding additional clusters does not result in the creation of a greater number of significantly large clusters. Hence, six clusters was the number used in the present study to assess canyon populations.

Canyon Classes	3 Cluster	4 Cluster	5 Cluster	6 Cluster	7 Cluster	8 Cluster	9 Cluster	10 Cluster	11 Cluster	12 Cluster	13 Cluster	14 Cluster	15 Cluster	16 Cluster	17 Cluster	18 Cluster	19 Cluster
1	78	113	47	37	41	18	22	41	22	32	17	18	17	16	11	14	14
2	736	1	1	1	3	3	5	13	13	11	12	11	18	10	12	10	11
3	3	700	507	143	0	0	0	1	2	0	1	3	8	10	7	8	3
4		3	260	614	367	118	177	0	114	34	11	0	1	3	4	3	3
5			2	22	395	551	4	69	0	490	0	8	5	0	1	4	1
6				0	11	8	461	455	0	238	151	0	0	1	101	0	13
7					0	103	9	225	495	1	0	188	152	158	2	0	0
8						1	139	5	157	5	323	15	3	16	55	105	126
9							0	8	7	6	274	443	310	0	0	17	28
10								0	7	0	6	9	284	358	285	0	1
11									0	0	18	0	5	227	290	318	11
12										0	4	118	0	3	6	255	371
13											0	4	19	0	0	73	205
14												0	4	12	19	0	5
15													0	3	21	3	0
16														0	3	4	3
17															0	3	11
18																0	2
19																	0

3.1 Principle Component Analysis

Geomorphic attributes of six canyon classes for the global ocean and for the Mediterranean (Tables 2 and 3, respectively) provide the basis for the assessment of the geomorphic attributes that characterize each type. A principle component analysis (PCA) was conducted on the global dataset

(Appendix A) to highlight the most important characteristics defining each canyon type (i.e. the longest and most coherent eigenvectors).

Table 2. Global canyon geomorphic statistics with standard deviations (SD). See text for description of variables.

Class	Number	Average area (km2) ± SD	Average delta depth (m) ± SD	Average mean depth (m) ± SD	Average length (km) ± SD	Average width (km) ± SD	Spacing (km) ± SD	Incisedness (%)
1	2968	325 ± 429	1,634 ± 683	2,648 ± 950	36 ± 26	13 ± 10	15.0 ± 55.0	5%
2	159	3,636 ± 2,704	2,851 ± 985	2,739 ± 642	163 ± 50	58 ± 30	13.7 ± 25.8	6%
3	2783	391 ± 558	2,026 ± 976	2,464 ± 1,071	41 ± 32	14 ± 12	8.25 ± 8.77	31%
4	3154	237 ± 309	1,578 ± 594	1,856 ± 968	30 ± 21	11 ± 9	9.64 ± 14.6	61%
5	378	1,754 ± 1,445	3,514 ± 1,124	2,056 ± 699	102 ± 49	40 ± 24	15.8 ± 35.3	72%
6	35	9,944 ± 5,417	3,669 ± 1,159	2,468 ± 627	286 ± 62	116 ± 43	11.4 ± 21.7	73%
Total	**9477**	**463 ± 1,041**	**1,833 ± 895**	**2,308 ± 1,037**	**41 ± 38**	**15 ± 16**	11.2 ± 33.3	**34%**

Table 3. Mediterranean canyon geomorphic statistics with standard deviations (SD). See text for description of variables.

Class	Number	Average area (km2) ± SD	Average delta depth (m)	Average mean depth (m) ± SD	Average length (km) ± SD	Average width (km) ± SD	Spacing (km) ± SD	Incisedness (%)
1	37	395 ± 436	1,565 ± 686	2,135 ± 820	44 ± 32	14 ± 9	16.0 ± 23.0	10%
2	1	3,510	3,107	1,646	159	47	9.51	8%
3	143	146 ± 187	1,679 ± 775	1,926 ± 717	26 ± 20	9 ± 7	4.86 ± 5.59	33%
4	614	135 ± 199	1,465 ± 518	1,497 ± 658	23 ± 17	8 ± 7	5.77 ± 9.62	63%
5	22	1,849 ± 1,326	2,482 ± 728	1,500 ± 397	100 ± 53	59 ± 24	11.1 ± 39.7	74%
6	0	-	-	-	-	-	-	-
Total	**817**	**199 ± 426**	**1,536 ± 612**	**1,601 ± 698**	**27 ± 25**	**10 ± 11**	6.22 ± 12.0	**55%**

The PCA for Class 1 canyons shows that they are characterized by length and width (and hence area; component 1; canyon length, width and depth are highly correlated) and by mean depth (Component 2). Class 1 canyons are globally the second most common type (n = 2,968), but in the Mediterranean Class 1 canyons constitute only a small population (n = 37). In the Mediterranean Class 1 canyons are located almost exclusively in the Ionian Sea, Gulf of Sidra region (Fig. 1); there are also two occurrences in the Tyrrhenian Sea and two in the eastern Mediterranean. Class 1 canyons exhibit a large spacing both globally and in the Mediterranean (Tables 2 and 3). Because of their small number, Class 1 canyons are not expected to significantly influence the average geomorphic character of Mediterranean canyons as a whole (Tables 2 and 3).

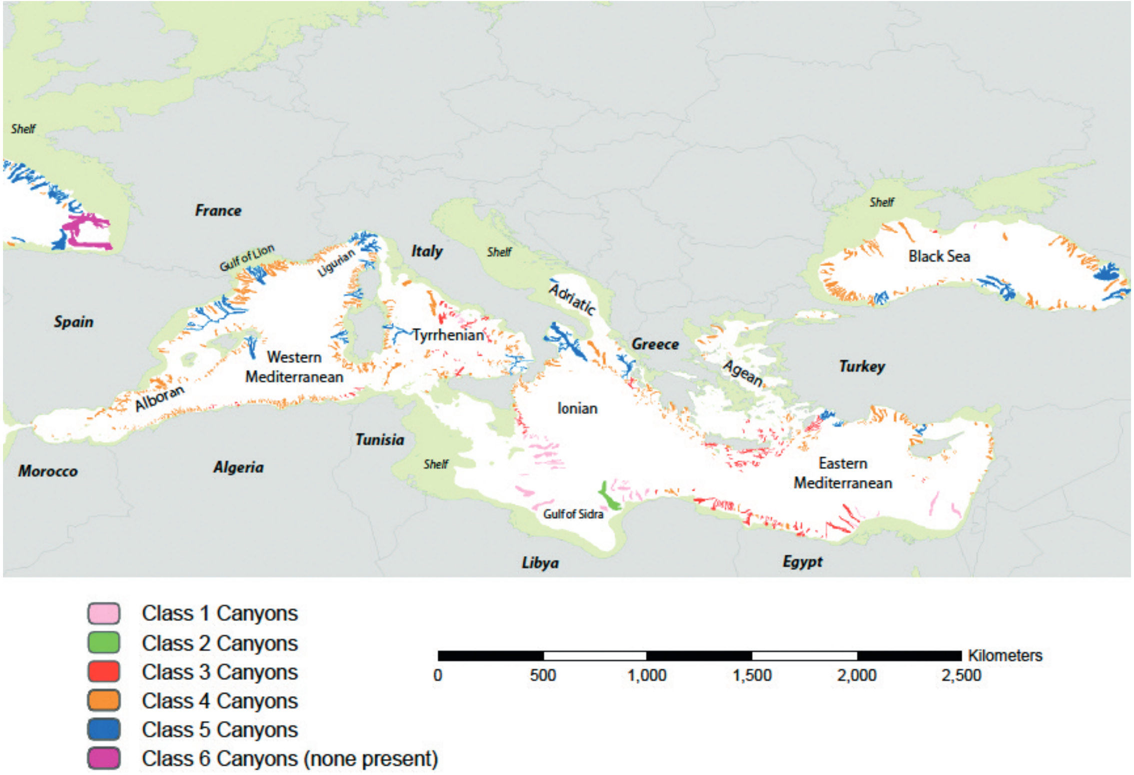


Figure 1. Distribution of canyon classes in the Mediterranean determined by multivariate statistical analysis of the global canyon data set as described in the text. Place names refer to discussion in the text. There are no Class 6 canyons in the Mediterranean Sea. The continental shelf area (after Harris *et al.*, 2014a) is shaded light green.

The PCA for Class 2 canyons shows that they are characterized by area, length and width (Component 1) and by depth range (delta depth, Component 2). Class 2 canyons are not a globally significant category (n = 159) and there is only one occurrence of Class 2 in the Mediterranean in the Gulf of Sidra (Fig. 1).

The PCA for Class 3 canyons shows that they are characterized by area, length and width (Component 1) and by the percentage of shelf incising canyons (incisedness) and canyon spacing (Component 2). Class 3 canyons are globally the third most common type (n = 2,968), and in the Mediterranean Class 3 canyons are the second most common type (n = 143; Tables 2 and 3). In the Mediterranean Class 3 canyons are located in the eastern Mediterranean off the coast of Egypt and south of Crete (Fig. 1). Class 3 canyons in the Mediterranean are significantly smaller in area than their global counterparts (146 ± 187 versus 391 ± 558 km^2, respectively) and also more closely spaced (4.86 ± 5.59 versus 8.25 ± 8.77 km^2, respectively) although their degree of incisedness in the Mediterranean (33%) is comparable to the global average (31%; Tables 2 and 3).

The PCA for Class 4 canyons shows that they are characterized by area, length and width (Component 1) and canyon spacing (Component 2); the percentage of shelf incising canyons (incisedness) is also important (Component 2). Class 4 canyons are globally the most common type (n = 3,154), and in the Mediterranean Class 4 canyons are also the most common type (n = 614; Tables 2 and 3). Class 4 canyons are widely distributed throughout the Mediterranean but are most common in the western Mediterranean and in the Black Sea (Fig.1). High concentrations occur in the Alboran Sea off the coast of Algeria, in the Gulf of Lion, the Ligurian Sea and in the western Black Sea. Class 4 canyons in the Mediterranean are significantly smaller in area than their global counterparts (135 ± 199 versus 237 ± 309 km^2, respectively) and they are also more closely spaced (5.77 ± 9.62 versus 9.64 ± 14.6 km^2, respectively). As in the case of

Class 3 canyons, the degree of incisedness of Class 4 canyons in the Mediterranean (63%) is comparable to the global average for that Class (61%; Tables 2 and 3).

The PCA for Class 5 canyons shows that they are characterized by length, width and area (Component 1) and by delta depth and mean depth (Component 2). Class 5 canyons are not common globally (n = 378), and there are only a small number of them in the Mediterranean (n = 22). Class 5 canyons exhibit a large spacing both globally and in the Mediterranean (Tables 2 and 3). Because of their small number, Class 5 canyons are not expected to significantly influence the geomorphic character of Mediterranean canyons as a whole (Tables 2 and 3).

Class 6 canyons are globally rare (n = 35) and there is no occurrence of a Class 6 canyon in the Mediterranean. Class 6 canyons are the world's largest, having the greatest mean area, length, width, mean depth, delta depth and percentage of incisedness. As noted by Harris *et al.* (2014a), the world's largest canyons tend to occur in the polar regions of the oceans.

3.2 Assessment of Class 4 canyons outside of the Mediterranean

From the above it can be seen that Class 4 canyons are numerically dominant and therefore exert a dominant influence on canyon geomorphic attributes that characterise the Mediterranean canyons. Therefore an assessment of the occurrence of Class 4 canyons beyond the Mediterranean is warranted. An assessment of locations around the world where large numbers of Class 4 canyons occur outside of the Mediterranean has been carried out using the focal variety tool in ArcGIS (Fig. 2) and the results are described here.

In the Celebes Sea – Timor Sea region (Fig. 2A) concentrations of Class 4 canyons occur around the island of Sulawesi in the Flores Sea and along the southern margin of the island of Java. Several Class 4 canyons feed into Bone Gulf in southern Sulawesi and are visible in multibeam imagery presented by Camplin and Hall (2014) who describe a regional Pliocene tectonic event that caused a "major influx of clastic sediments from the north and the development of a southward-flowing canyon system". Class 3 canyons dominate in this region overall (Class 4 canyons are regionally subordinate to Class 3) and Class 5 canyons also occur in significant numbers.

Concentrations of Class 4 canyons occur off the east coast of Taiwan extending northwards into the East China Sea and around the Okinawa Trough (Japan; see Oiwane *et al.*, 2011); another group occurs on both the east and west coasts of the island of Kalusunan in the Philippines (Fig. 2B). These groups of Class 4 canyons are separated by a cluster of Class 3 canyons, located between Taiwan and Kalusunan.

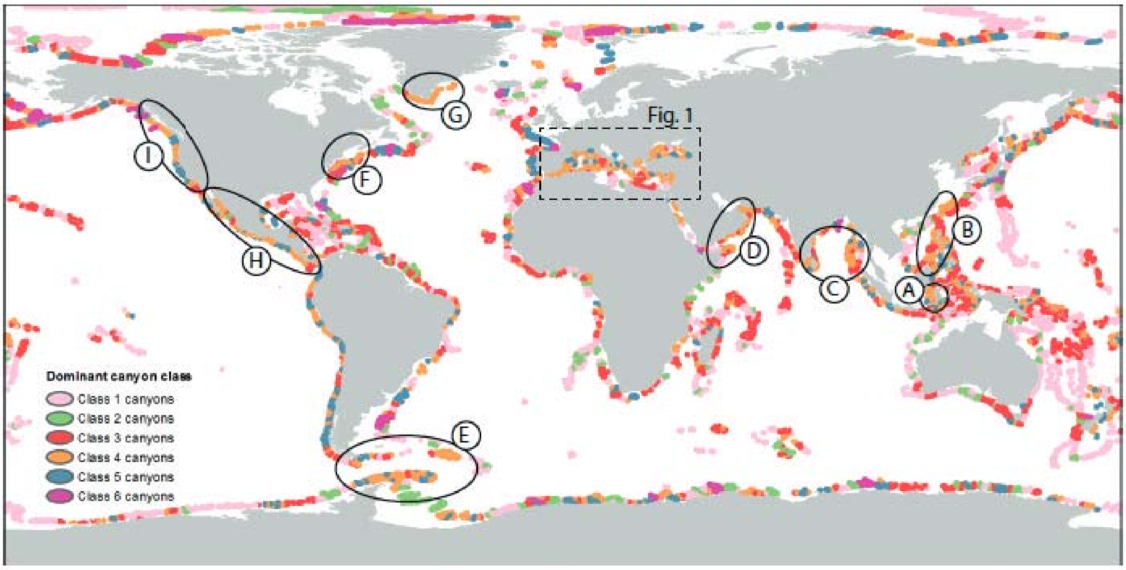


Figure 2. Map showing the global distribution of canyon classes produced using focal statistics. The majority canyon type over a 100 km moving window was calculated in ArcGIS. The map illustrates different regions containing local concentrations of Class 4 canyons (see text for details).

In the Bay of Bengal, Class 4 canyons outnumber all other classes and dominate the region (Fig. 2C). They are most common around the Andaman Islands and Sri Lanka. Other canyon classes are much less common and there are only a few groups of Class 3 and isolated occurrences of Class 5 canyons. The tectonic setting of this region is complex (Curray, 2014) since the Andaman Islands side of the Bay of Bengal is considered an active plate margin whereas Sri Lanka is considered to be a passive margin (Fig 3).

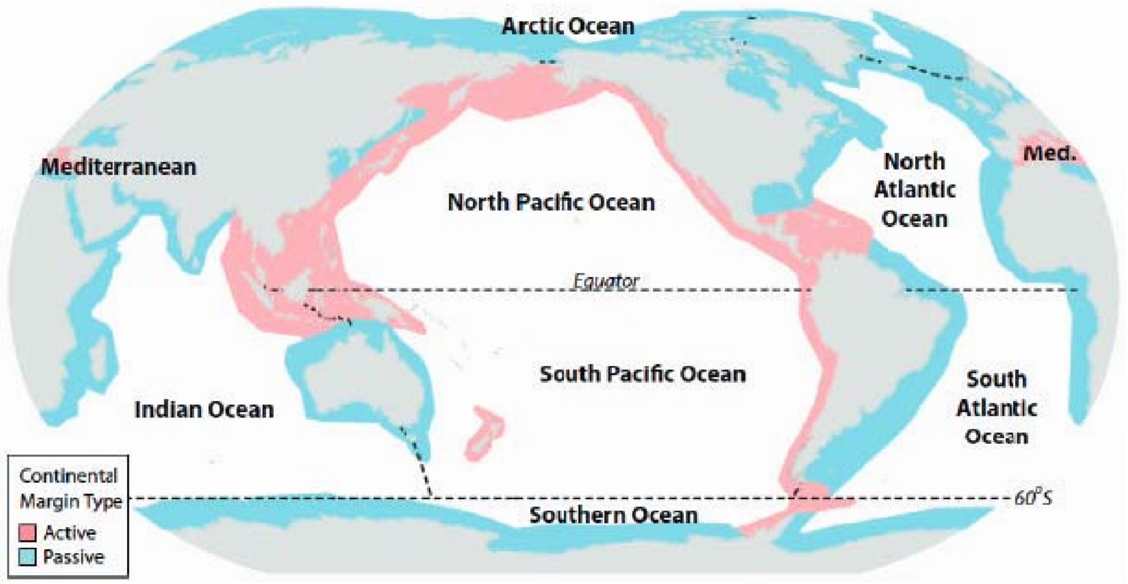


Figure 3. Map showing the global distribution of active and passive plate margins.

Further east adjacent to the Arabian Peninsula and Gulf of Aden, Class 4 canyons dominate the continental margin, with groups of Class 4 canyons interspersed with one or two Class 3 canyons (Fig. 2D). Here again the tectonic setting is complex with active seafloor rifting in the Gulf of Aden and plate collision between India and the Arabian Plate (Fournier *et al.*, 2010).

Drake Passage contains concentrations of Class 4 canyons (Fig. 2E), especially off the southern coast of Tierra del Fuego, adjacent to the Antarctic Peninsula and around the island of South Georgia. In this region Class 4 canyons outnumber all other Classes. They are interspersed with some Class 5 canyons and with lesser numbers of Class 3 canyons.

Several large groups of Class 4 canyons are located off the coast of the eastern United States (Fig. 2F) and southern Greenland (Fig. 2G), providing examples of their occurrence along a passive continental margin. One continuous group of around thirty Class 4 canyons is located offshore of Chesapeake Bay and another large group is located east of Cape Cod (Shepard, 1981; Mitchell, 2008). These groups are interspersed with isolated Class 5 and 6 canyons and small groups of Class 3. A group of about 18 Class 4 canyons extend without interruption along the southern and southeastern margins of Greenland.

Concentrations of Class 4 canyons occur in the Gulf of California, around the southern tip of the Baja California Peninsula and as an extensive semi-continuous group, interspersed with individual, isolated Class 5 canyons, extending along the western coast of Mexico (Reimnitz and Gutiérrez-Estrada, 1970) from Puerto Vallarta southwards to Guatemala, El Salvador and Nicaragua (Fig. 2H). Class 4 canyons also dominate along large sections of the eastern margin of South America (Fig. 2).

In the northeast Pacific, along the western coasts of British Columbia (Canada) and the United States, Class 4 canyons dominate over large areas (Fig. 2I). One continuous group extends along the entire coast of British Columbia (apart from one large Class 6 canyon) and a semi-continuous group extends northwards from San Francisco to the Columbia River mouth, interspersed with a few Class 5 canyons (Shepard, 1981). Tectonic processes are thought to have exerted control on the geomorphology of some British Columbia canyons (Harris *et al.*, 2014b) and on some California canyons (Le Dantec *et al.*, 2010) but not on others (Gardner *et al.*, 2003).

4. DISCUSSION

4.1 Significance of Mediterranean canyon statistics

Out of 817 canyons in the Mediterranean, 614 (over 75%) are classified here as Class 4, much more than the global average of Class 4 comprising 33% of all canyons. Therefore, canyon geomorphologic statistics in the Mediterranean are strongly governed by this Class and the overall attributes of small area, short length, narrow width and close canyon spacing are attributable to the dominance of Class 4 canyons in the Mediterranean region.

An assessment of other locations around the world where large numbers of Class 4 canyons occur (Fig. 2) suggests a pattern of occurrence: Class 4 canyons appear to occur more commonly along active plate margins compared with passive margins (Fig. 3). In fact the number of Class 4 canyons occurring along active margins (n = 1,970) is much greater than the number found along passive margins (n = 908); i.e. 68% of Class 4 canyons occur on active margins. But there is considerable variation regionally as described above.

Some other clear associations are that Classes 3, 4 and 5 canyons are often found together in the examples studied (Fig. 2). However, whereas Class 3 and 4 canyons tend occur as discrete clusters of five or more, Class 5 canyons are often solitary and occur interspersed with Class 4 canyons. Controls of tectonism and sediment input exhibit broad variations and there is no single process that appears to dominate in the formation of Class 4 canyons.

4.2 Relevance of canyon geomorphology in canyon evolution

Shepard (1981) summarized the two main processes attributed to canyon formation: i) mass wasting and retrograde slumping of the continental slope and ii) erosion by turbidity currents sourced from the continental shelf. These two processes (Fig. 4) are not mutually exclusive and are probably contemporaneous and spatially congruous on many slopes, but considering the two processes separately provides a framework to interpret the statistical data we now have available on canyon geomorphic attributes.

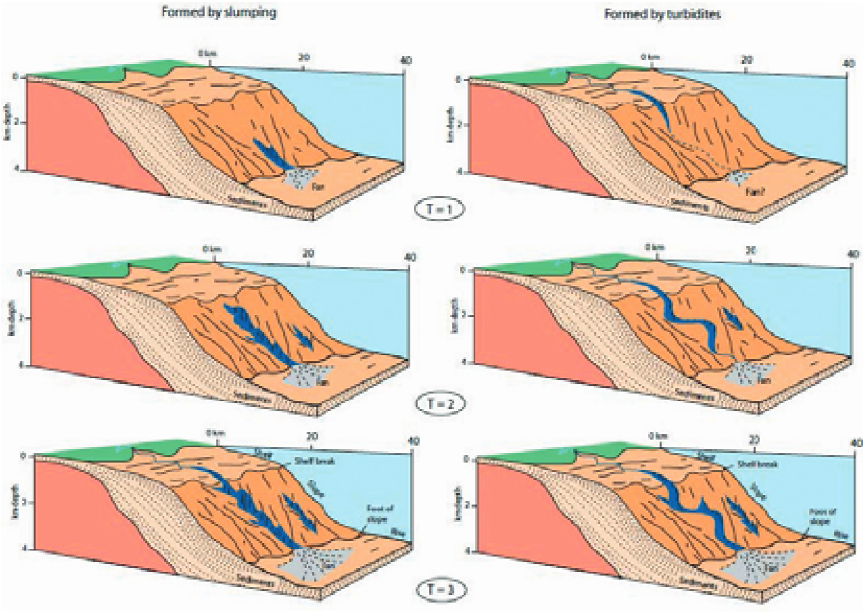


Figure 4. Schematic diagrams showing evolution of submarine canyons over three time slices (T1 to T3) by two processes: i) mass wasting and retrograde slumping of the continental slope and ii) erosion by turbidity currents sourced from the continental shelf. The meandering course of deeply incised, mature canyon thalwegs formed by erosion by turbidites was suggested by Gee *et al.* (2007).

Modelling has revealed the importance of headward erosion driven by sediment flow downcutting, in which tributaries are the precursors of larger submarine canyon systems (Pratson and Coakley, 1996). Enlargement by slumping has been shown to explain the morphology of some canyon systems (Sultan *et al.*, 2007). Fluid escape along a section of continental slope prone to slump-failure may theoretically produce a self-organised canyon (Orange *et al.*, 1992).

The two processes (Fig. 4), taken as a model for canyon formation, make at least three predictions that can be tested:

1. The occurrence of shelf-incising canyons should correlate approximately with regionally averaged sediment discharge to the coast.
2. Shelf incising canyons are on average larger than blind canyons because they are only formed towards the end of the evolutionary cycle involving incipient blind canyons.
3. The number of blind canyons should exceed the number of shelf incising canyons because shelf incising canyons are only formed towards the end of the evolutionary cycle involving (often several) incipient blind canyons.

Prediction Number 1 was addressed by Harris and Whiteway (2011) who plotted modeled sediment discharge data (Ludwick and Probst, 1998) versus the percentage of shelf incising canyons for all non-polar margins on earth (Fig. 5). The resulting plot demonstrates that a strong relationship (r = 0.68) exists between these parameters, as the proposed model predicts.

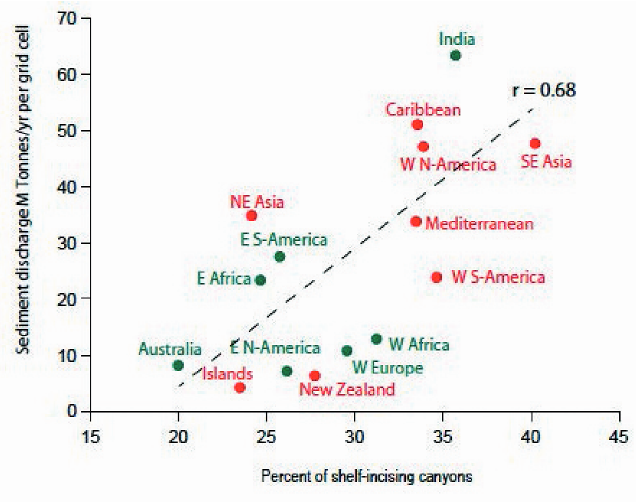


Figure 5. Plot of the fraction of canyons occurring in each geographic region (excluding the Arctic and Antarctic) that incise the continental shelf (modified from Harris and Whiteway, 2011) versus the rate of sediment discharge modelled by Ludwig and Probst (1998), measured in million tonnes per year per grid cell (2o Lat.itude by 2.5o Longitude). Sediment discharge values plotted here are estimated from Ludwig and Probst (1998; their figure 11) by taking the average value for modelled grid cells occurring within the specified geographic regions. The linear correlation coefficient r = 0.68 for the data shown. Active regions are shown in red and passive in green.

The second and third predictions can be tested based on statistical data (Table 4) published by Harris *et al.* (2014). The data show that the average size of shelf- incising canyons is more than twice that of blind canyons, as per prediction number 2. Furthermore, blind canyons outnumber shelf-incising canyons by a ratio of more than 3 to1 (see Table 4), which supports prediction number 3. What can also be seen is that the statistics are consistent across all ocean regions; the average size of shelf- incising canyons exceeds that of blind canyons, and blind canyons outnumber shelf-incising canyons in every ocean region. The Mediterranean is no exception to this globally consistent pattern (Table 4).

Table 4. Statistics on shelf incising and blind canyons (from Harris *et al.,* 2014). The data show that blind canyons outnumber shelf incising canyons by a ratio of more than 3 to1, whilst the average size of shelf incising canyons is more than twice that of blind canyons.

Ocean	**All canyons No.**	**Self-incising No.**	**Blind canyon No.**	**Self-incising average size km²**	**Blind canyon average size km²**
Arctic Ocean	404	75	329	2,160	600
Indian Ocean	1,590	295	1,295	754	415
Mediterranean Black Sea	817	307	510	307	134
North Atlantic	1,548	293	1,255	997	355
North Pacifie	2,085	489	1,596	751	281
South Atlantic	453	73	380	894	594
South Pacifie	2,009	368	1,641	584	292
Southern Ocean 5	71	176	395	1,104	949
All Oceans	9,477	2,076	7,401	777	375

CONCLUSIONS

The unique geomorphic attributes of Mediterranean canyons are due to the dominance of Class 4 canyons in that region. Apart from their occurrence on active margins, there is no other obvious common factor among the global occurrences of Class 4 canyons (Fig. 2) that has emerged from our assessment. The identification of other factors (apart from their occurrence on active margins) that may control the formation of Class 4 canyons awaits future research.

The model for canyon formation put forward by Shepard (1981) includes two basic processes: i) the mass wasting and retrograde slumping of the continental slope and ii) erosion by turbidity currents sourced from the continental shelf. This model provides the basis for making three predictions that have been tested using available data:

1. the occurrence of shelf-incising canyons correlates approximately with regionally averaged sediment discharge to the coast;

2. shelf incising canyons are on average larger than blind canyons; and

3. the number of blind canyons exceeds the number of shelf incising canyons.

The available data are consistent with these three predictions. Furthermore, the geomorphic data for the Mediterranean region shows that the average size of shelf- incising canyons exceeds that of blind canyons, and blind canyons outnumber shelf-incising canyons.

---

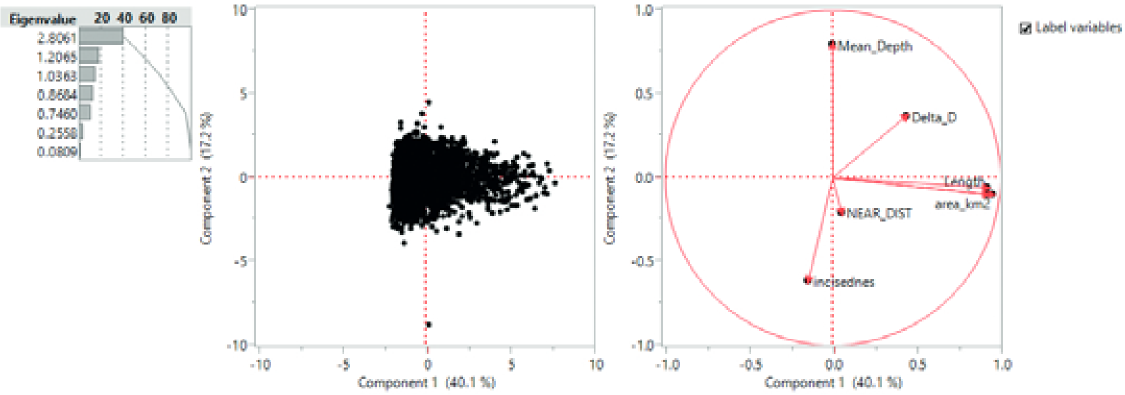
* this chapter is to be cited as:

Harris P.T., Macmillan-Lawler M. 2015. Geomorphology of Mediterranean submarine canyons in a global context – Results from a multivariate analysis of canyon geomorphic statistics. pp. 23 - 35 In CIESM Monograph 47 [F. Briand ed.] Submarine canyon dynamics in the Mediterranean and tributary seas - An integrated geological, oceanographic and biological perspective, 232 p. CIESM Publisher, Monaco.

Appendix A. Principal Component Analysis, six classes

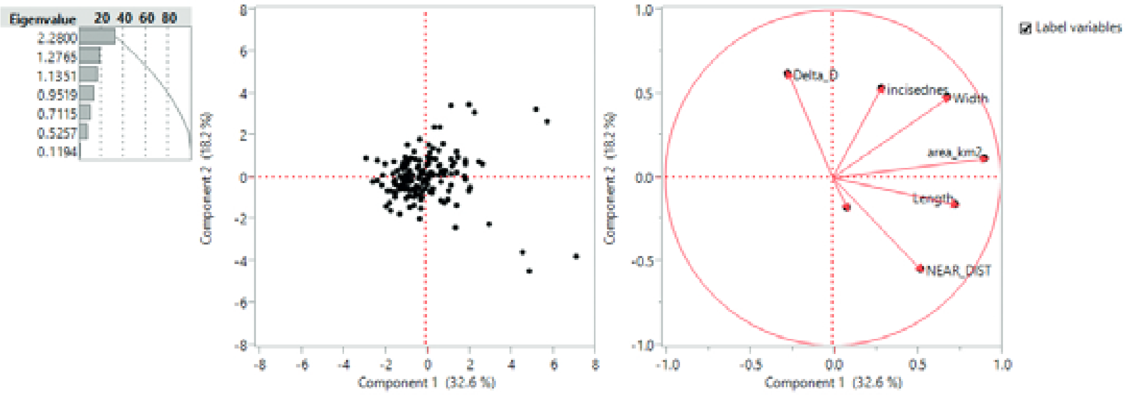
Class 1

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.951	-0.102	0.037	-0.084	0.162	-0.022	-0.224
Delta_D	0.440	0.370	-0.343	0.480	-0.567	-0.027	-0.022
Mean_Depth	-0.002	0.791	0.070	0.320	0.518	0.003	0.006
Length	0.917	-0.058	0.002	-0.029	0.053	0.375	0.107
Width	0.919	-0.098	0.010	-0.046	0.110	-0.337	0.136
Spacing	0.052	-0.204	0.863	0.442	-0.125	-0.002	-0.002
incisednes	-0.146	-0.616	-0.410	0.575	0.317	0.011	0.000



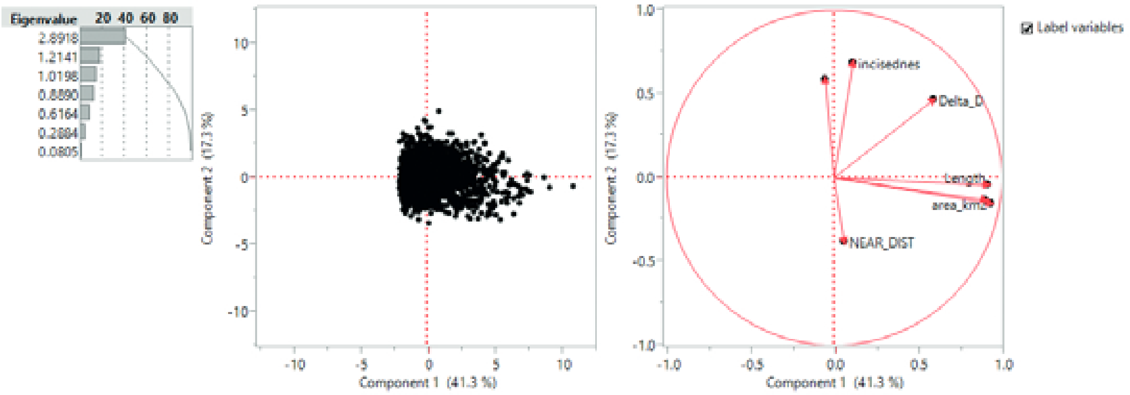
Class 2

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.909	0.113	0.156	-0.235	-0.037	-0.139	-0.247
Delta_D	-0.264	0.623	0.414	0.266	0.520	-0.175	-0.019
Mean_Depth	0.087	-0.181	0.783	0.443	-0.353	0.162	-0.004
Length	0.736	-0.161	-0.177	0.430	-0.026	-0.446	0.130
Width	0.689	0.477	0.235	-0.412	-0.043	0.182	0.196
Spacing	0.525	-0.550	0.020	0.122	0.546	0.330	0.008
incisednes	0.291	0.537	-0.490	0.511	-0.125	0.329	-0.053



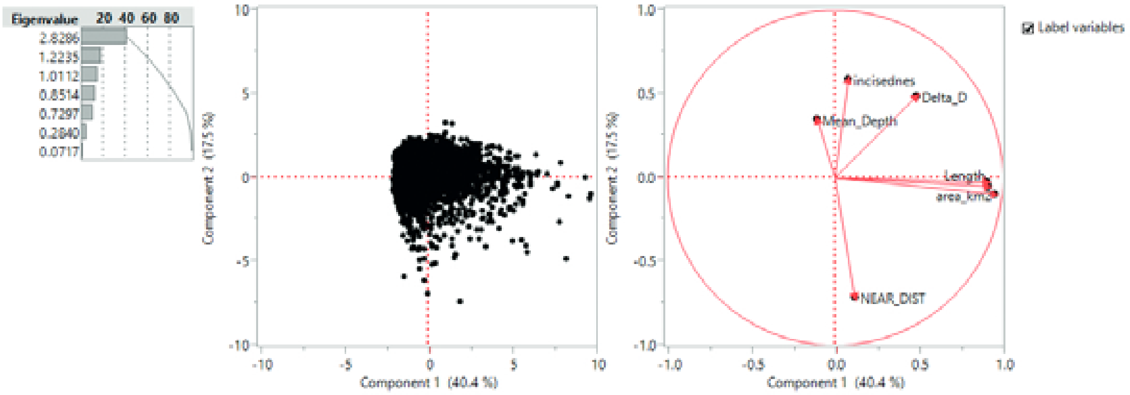
Class 3

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.936	-0.155	0.034	-0.053	-0.218	-0.011	-0.219
Delta_D	0.595	0.467	-0.120	-0.031	0.641	0.012	-0.035
Mean_Depth	-0.051	0.584	0.498	-0.617	-0.167	0.020	0.008
Length	0.911	-0.043	0.003	-0.033	-0.095	-0.376	0.129
Width	0.901	-0.133	-0.005	-0.027	-0.095	0.382	0.121
Spacing	0.059	-0.379	0.858	0.247	0.234	-0.009	0.000
incisednes	0.114	0.684	0.140	0.665	-0.239	0.018	0.000



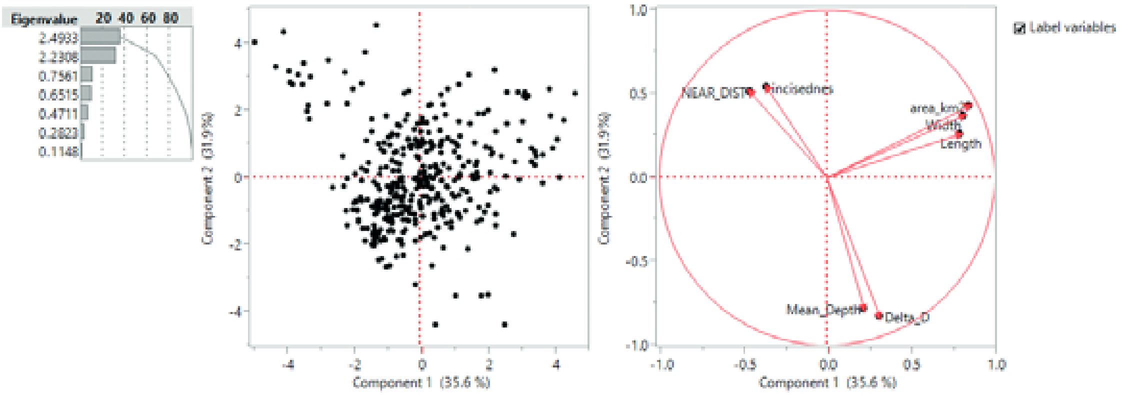
Class 4

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.950	-0.097	0.022	-0.011	-0.207	0.018	-0.210
Delta_D	0.487	0.488	0.136	-0.067	0.707	0.039	-0.024
Mean_Depth	-0.105	0.345	0.845	0.332	-0.214	0.009	0.004
Length	0.909	-0.027	0.034	0.004	-0.063	-0.396	0.103
Width	0.911	-0.051	0.004	-0.050	-0.152	0.353	0.129
Spacing	0.118	-0.715	0.068	0.611	0.310	0.024	0.001
incisednes	0.079	0.586	-0.522	0.600	-0.135	0.007	0.000



Class 5

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.850	0.425	0.065	0.133	0.092	0.012	-0.258
Delta_D	0.316	-0.827	0.070	0.160	0.190	0.386	0.019
Mean_Depth	0.223	-0.783	0.170	0.458	-0.064	-0.308	0.004
Length	0.791	0.258	-0.152	0.149	-0.489	0.111	0.109
Width	0.810	0.369	0.087	-0.050	0.389	-0.109	0.185
Spacing	-0.460	0.513	-0.417	0.566	0.166	0.056	0.025
incisednes	-0.359	0.537	0.717	0.231	-0.066	0.104	0.036



Class 6

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.644	0.569	0.338	-0.249	0.120	0.201	-0.174
Delta_D	-0.494	0.653	0.055	0.322	0.377	-0.281	-0.050
Mean_Depth	-0.734	0.467	0.156	0.204	-0.047	0.411	0.082
Length	0.309	-0.286	0.876	0.101	0.160	-0.053	0.129
Width	0.585	0.654	-0.337	-0.251	0.119	-0.025	0.198
Spacing	0.530	-0.413	-0.349	0.502	0.361	0.210	-0.008
incisednes	0.548	0.408	0.064	0.581	-0.429	-0.086	-0.006