Fan deltas classification coupling morphometric analysis and artificial neural networks: The case of NW coast of Gulf of Corinth, Greece*

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ABSTRACT: This study is an attempt to classify fourteen Late Holocene coastal alluvial fans formed by high-gradient braided streams and torrents that discharge into the Gulf of Corinth along its northwestern coast. The morphology of the fans and their catchments is quantitatively described through morphometric parameters estimated using Geographical Information Systems techniques. The relationships between geomorphological features of the fans and their drainage basins were also examined. Self Organising Maps (SOM), were used in order to investigate clustering tendency of alluvial fans according to both qualitative data and morphometric variables. The results of the analysis using the method of Artificial Neural Networks (ANNs) exposed correlation relationships among these characteristics, and revealed alluvial fan types according to the predominant fan formation processes.

Four morphologically different fan types were recognized based on their geomorphological characteristics. Large basins appear to produce large gently sloping fluvial dominated fans with a rapidly shifting shoreline while torrents with small rough basins have formed steep debris flow dominated fans. A strong positive relation was found between the size of the fan and the drainage basin area while the relation between drainage area and fan slope was negative and moderately strong. The power functions that describe these relationships resemble those proposed by other authors for arid and humid temperate regions.
Key-words: *Fan deltas, geomorphology, morphometry, artificial neural networks, Gulf of Corinth, Greece.*

ΠΕΡΙΛΗΨΗ: Σκοπός της εργασίας αυτής είναι η ταξινόμηση δεκατεσσάρων παράκτιων αλλουβιακών ριπιδίων, ηλικίας Ανώτερου Ολόκαινου που έχουν διαμορφωθεί στις εκβολές χειμάρρων με διακλαδιζόμενες κοίτες κατά μήκος των βόρειων ακτών του δυτικού Κορινθιακού κόλπου. Η ποσοτική περιγραφή της μορφολογίας των ριπιδίων και των αντίστοιχων λεκανών απορροής περιλαμβάνει την εκτίμηση μορφομετρικών παραμέτρων με τη χρήση των Γεωγραφικών Συστημάτων Πληροφοριών. Επιπλέον, εξετάστηκαν οι σχέσεις μεταξύ των γεωμορφολογικών χαρακτηριστικών των ριπιδίων και των λεκανών απορροής των υδρογραφικών τους δικτύων. Χρησιμοποιήθηκαν επίσης, αυτοοργανούμενοι χάρτες Kohonen (SOM), προκειμένου να διερευνηθεί η δυνατότητα ομαδοποίησης των αλλουβιακών ριπιδίων τόσο μέσω των ποιοτικών χαρακτηριστικών, όσο και μέσω των μορφομετρικών μεταβλητών. Τα αποτελέσματα της ανάλυσης με τη μέθοδο των τεχνητών νευρωνικών δικτύων (ANNs) έδειξαν τη συσχέτιση μεταξύ των χαρακτηριστικών αυτών και ανίχνευσαν ομάδες αλλουβιακών ριπιδίων σύμφωνα με τις κυρίαρχες διεργασίες σχηματισμού και διαμόρφωσής τους.

Αναγνωρίστηκαν τέσσερεις ομάδες ριπιδίων με βάση τα γεωμορφολογικά τους χαρακτηριστικά. Μεγάλες λεκάνες απορροής έχουν σχηματίσει μεγάλης έκτασης και μικρής κλίσης ριπίδια στα οποία κυριαρχούν ποτάμιες διεργασίες και των οποίων η ακτογραμμή μετατοπίζεται κυρίως στον άμεσο χώρο των εκβολών. Αντίθετα μικρές απόκρημνες λεκάνες, όπου κυριαρχούν διεργασίες κίνησης υλικών λόγω βαρύτητας, έχουν διαμορφώσει μικρής έκτασης και μεγάλης κλίσης ριπίδια. Η συσχέτιση μεταξύ της έκτασης των ριπιδίων και της έκτασης των αντίστοιχων λεκανών είναι θετική και ισχυρή ενώ η συσχέτιση της έκτασης της λεκάνης με την κλίση του ριπιδίου είναι αρνητική και σχετικά καλή. Οι εκθετικές εξισώσεις που περιγράφουν τις σχέσεις αυτές μοιάζουν με ανάλογες που έχουν διαπιστωθεί για ριπίδια σε άνυδρα περιβάλλοντα.
Λέξεις-κλειδιά: *δελταϊκά ριπίδια, γεωμορφολογία, μορφομετρία, τεχνητά νευρωνικά δίκτυα, Κορινθιακός κόλπος,Ελλάδα.*

INTRODUCTION

Alluvial fans are prominent depositional landforms developed where steep high power channels enter zones of reduced stream power and serve as a transitional environment between degrading upland areas and adjacent lowlands (HARVEY, 1997). Alluvial fans are subareal features, however if they extend into water, like the fans of this study, they are known as fan deltas. Typically, they range in scale from axial lengths of tens of meters to tens of kilometers. Their morphology resembles a cone segment with constant or slightly concave slopes that typically range from less than 25 degrees at the head or apex of the fan, to less than a degree at the terminus or toe (DENNY, 1965; BULL, 1977). Three main factors are necessary for optimal alluvial fan development including topography conducive to the formation of such landforms, sediment availability and production in the drainage basin and a medium or mechanism for transporting sediment from the drainage basin to the site of fan construction (BLAIR & Mc PHERSON, 1994).

* Ταξινόμηση δελταϊκών ριπιδίων συνδυάζοντας τη μορφομετρική ανάλυση και τα τεχνητά νευρωνικά δίκτυα: η περίπτωση των βορειοδυτικών ακτών του Κορινθιακού κόλπου

Alluvial fans of various geographical settings have been thoroughly investigated around the world as these landforms occur in any climatic environment like temperate mountain regions (e.g. KOSTASCHUCK *et al.*, 1986; GILES, 2010), humid temperate (e.g. KOCHEL, 1990) and even humid tropical environments (e.g. KESEL & SPICER, 1985). In the early 1960's alluvial fan researchers began to use quantitative data to determine the processes controlling fan development (LECCE, 1990). Fan-basin relationships became a fundamental concept and several empirical models were utilized to describe the rates of change between certain characteristics of an alluvial fan and its drainage basin. Several studies explore the relation between the size of fans and their contributing basins to understand the mechanisms of fan construction (BULL, 1964, 1972, 1977; DENNY, 1965; HOOKE, 1968; CHURCH & MARK, 1980). Other studies of fan-basin morphometric relations focus on differentiation between debris flow and fluvial dominated fans (KOSTASCHUK *et al.*, 1986; DE SCALLY *et al.*, 2001; DE SCALLY & OWENS, 2004; GILES, 2010). GILES (2010) successfully proposed the use of alluvial fan volume to represent fan size in morphometric studies.

The aim of this study is the classification of fourteen fans, located on the northern coast of the Gulf of Corinth in Central Greece according to their morphological features, which correspond to the dynamic factors affecting their formation and evolution, utilizing morphometry and Artificial Neural Networks (ANNs). For this purpose qualitative geomorphological observations and quantitative estimations of morphometric variables as well as comparison of the distinct parameters characteristic of the coastal fans and their catchments were performed. ANNs were used in order to investigate correlation relationships among morphometric parameters and quantitative characteristics. The application of ANNs revealed also four fan type clusters in the data set describing morphometric parameters of the fans and their feeder systems. These clusters have a clear geomorphological meaning as they correspond to particular alluvial fan types.

ARTIFICIAL NEURAL NETWORKS (ANNs)

Artificial neural networks (ANNs) are computer based tools which mimic the knowledge acquisition and organizational skills of the human brain cells. They consist of numerous, simple processing units the "neurons" that can be programmed for computation. They can be trained to store, recognize and associatively retrieve patterns or database entries from large data sets; to solve large optimization problems; to estimate continuous functions when the form of the function is not known. This is why they are usually called model-free mapping devices.

ANNs are capable of learning; that is, they can be trained to improve their performance by either supervised or unsupervised learning. Unsupervised neural networks, used in this paper, are trained by letting the network continually adjust itself to new inputs. They uncover nonlinear relationships within data and can define classification schemes that adapt to changes in new data and finally reveal new patterns. This is one of the reasons why numerous papers are written applying ANN in Earth sciences. Among the advantages of neural networks is that they conserve the complexity of the systems they model because they have complex structures themselves. They also, encode information about their environment in a distributed form and have the capacity to self-organize their internal structure.

Self Organsing Maps (SOM), originally introduced by KOHONEN (1995), are unsupervised neural networks formed from neurons located on a regular usually 2-dimensional regular planar array grid. SOM are capable of mapping high-dimensional similar input data into clusters close to each other, according to their similarity relations.

SOM eventually settles into a map of stable zones, the neighbours. Each zone is effectively a feature classifier, so the graphical output of this kind of analysis could be characterized as a type of feature map of the input space (n-dimensional input data). The trained ANN represents the individual zones by the blocks of similar color. Any new, previously unseen input vectors presented to the network will stimulate nodes in the zone (cluster) with similar weight vectors. For the interested reader SOM is thoroughly presented in VESANTO (1999) and VESANTO & ALBONIEMI (2000). All the calculations in this study were performed using Matlab v.7 software applying SOM Toolbox 2.0 (VESANTO, 1999).

The training process of SOM network is presented in the APPENDIX.

STUDY AREA

The studied coastal alluvial fans are situated on the northwestern coast of the Gulf of Corinth (Fig. 1). Most of them are relatively steep fan deltas formed by high-gradient torrents of ephemeral flow that discharge into the Gulf. Since the configuration of the studied fan deltas is the result of the interaction between the lithology of the geological formations within the drainage basin, the climate conditions and the tectonic regime of the broader area, the physio-geographic characteristics of both the catchment areas and the receiving basin (Gulf of Corinth) are given below.

The basic structural pattern of the broader area of the drainage basins was established during the Alpine folding. The drainage basins are dominated by the geological formations of the geotectonic zones of Parnassos-Ghiona, Olonos-Pindos, Ionian and the Transitional zone between those of Parnassos-Ghiona and Olonos-Pindos (Fig. 2). The majority of the catchments consist of the Olonos-Pindos zone formations which are represented by platy limestones of Jurassic-Senonian age and flysch lithological sequences (mainly sandstones and shales) of Upper Cretaceous - Eocene. The easternmost basins (Eratini and part of Stournarorema) are made up of Tithonian to Senonian limestones of the Parnassos-Ghiona zone and the Transitional sedimentary series

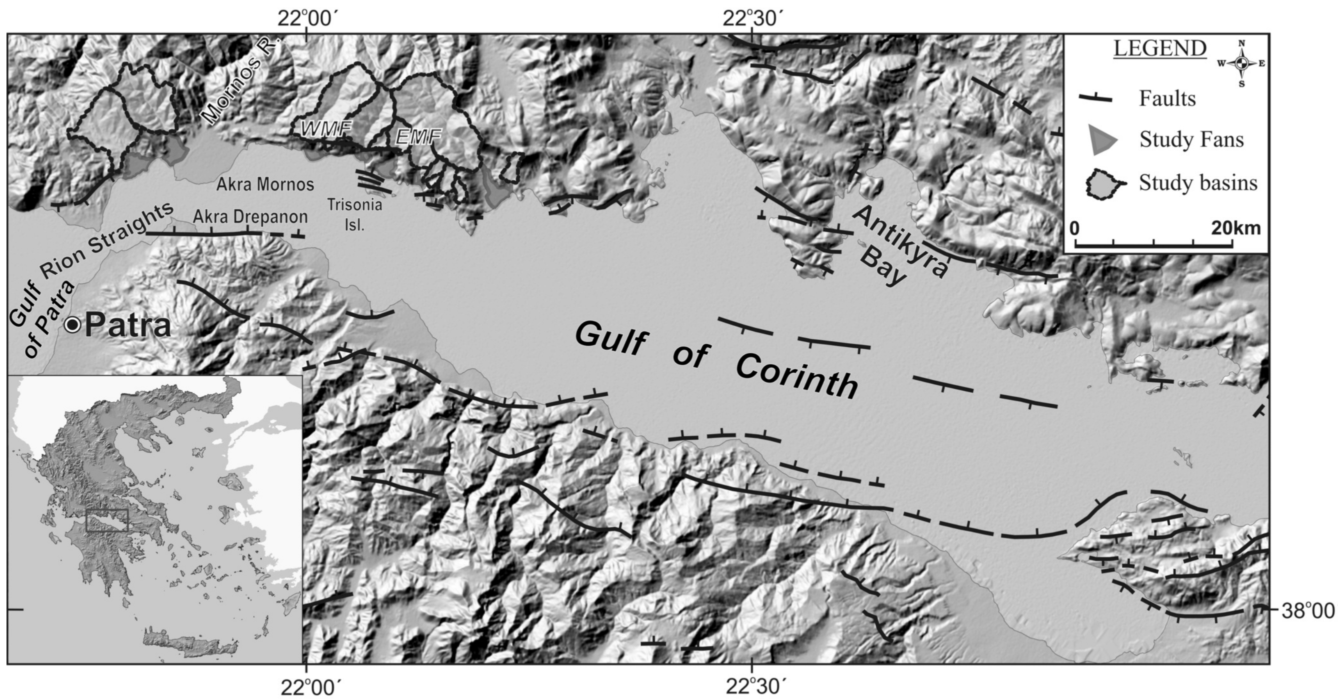

Fig. 1. Map of the Gulf of Corinth showing the main faults of the broader area and the location of the studied fans and their catchments. EMF and WMF stands for east and west Marathias fault segment respectively (faults based on ARMIJO *et al.*, 1996, Marathias fault based on GALLOUSI & KOUKOUVELAS, 2007).

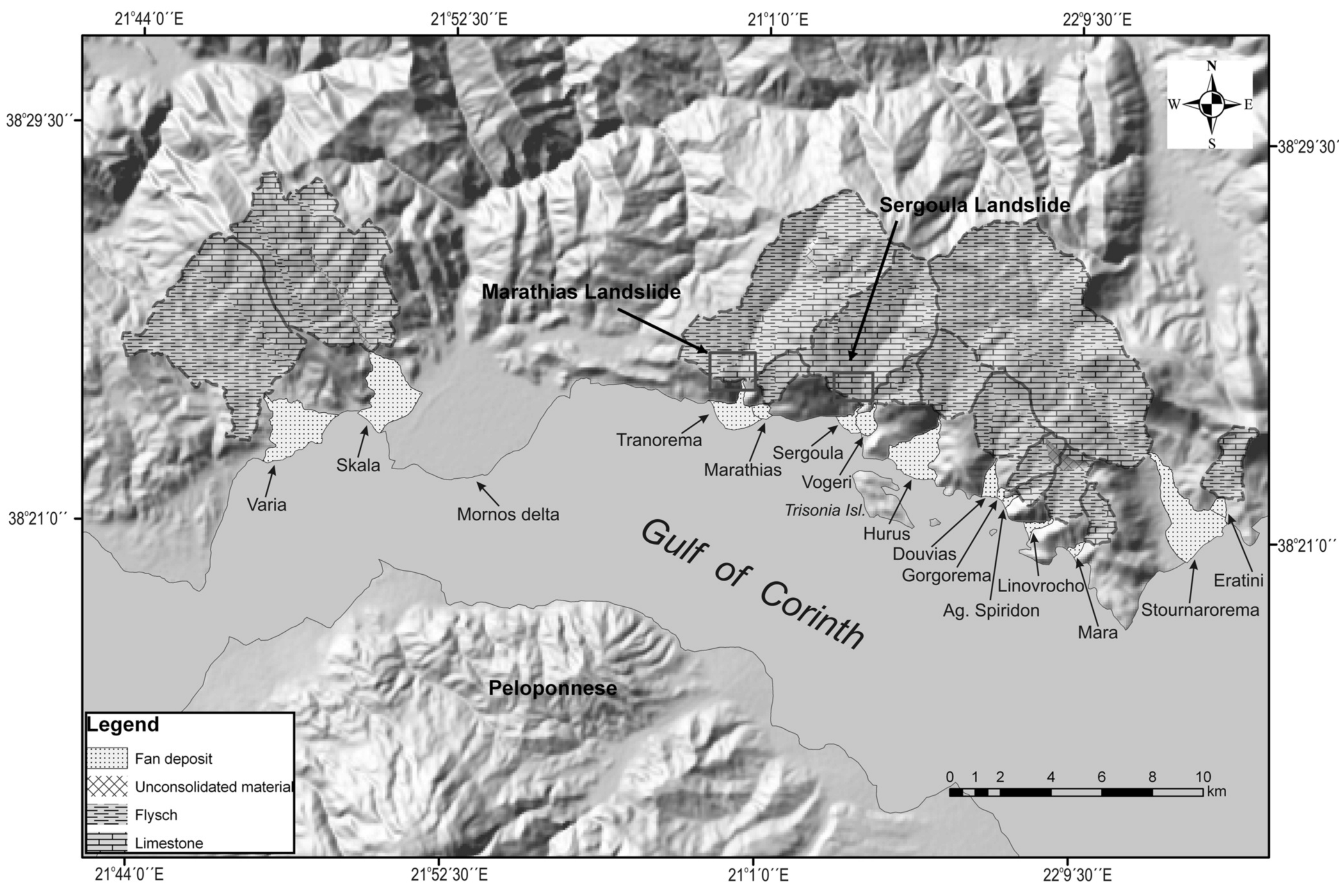

Fig. 2. Simplified lithological map of the drainage basins of the coastal fans under study.

(limestones of Upper Triassic to Paleocene age and sandstones and shales of the Paleocene - Eocene flysch). Part of the westernmost Varia drainage system drains flysch formations (mainly marls, sandstones and conglomerates) of the Ionian zone. Tectonically the area is affected by an older NW-SE trending fault system, contemporaneous to the Alpine folding and a younger one having an almost E-W direction.

The Gulf of Corinth is an N100° E oriented elongated graben, 150 km long which separates the Peloponnese from Continental Greece (Fig. 1). It is a major Late Cenozoic asymmetric graben (BROOKS & FERENTINOS, 1984; ARMIJO *et al.*, 1996) bounded by systems of very recent roughly E-W normal faults, located mainly along the southern coast, intersecting the structural grain of the Hellenides at almost right angles (KOKKALAS *et al.*, 2006; ZYGOURI *et al.*, 2008). It is characterized by high levels of seismicity and is currently extending at high rates. Particularly in its westernmost part, where the study area is located, deformation rates attain a value of 14 ± 2 mm/yr (BRIOLE *et al.*, 2000). Frequent seismic activity in the region is responsible for numerous submarine mass movements especially at the prodelta steep slopes (POULOS *et al.*, 1996; HASIOTIS *et al.*, 2006). Extension in the Gulf is accommodated by two main fault trends in an ENE to NE and a WNW-ESE. Faults are numerous on both sides of the Gulf. Active faulting on the southern side has resulted in more than 950 m of Pleistocene uplift of the mountains in the south (ARMIJO *et al.*, 1996). However, some of the south dipping faults located on (or near) the northern shore are still active (MORETTI *et al.*, 2003). Most significant among them are the normal faults located in the broader area of Trizonia Island and the Marathias fault (Fig. 1). The latter is a WNW-trending fault with a total strike length of ~17 km and consists of two prominent segments. The existence of striated fault planes on this strand and the capture of streams along its trace suggest that Marathias fault is active and a significant part of its deformation is accommodated during earthquake activity (GALLOUSI & KOUKOUVELAS, 2007). Tranorema and Marathias fans lie on the hanging wall of the western segment while the fans of Sergoula and Vogeri have been affected by the east segment of the fault. Along the Marathias fault trace a series of earthquake triggered landslides are concentrated mainly at the near tip areas. The most significant slides are those of Marathias (photo 1) at the west fault segment and Sergoula at the east one. GALLOUSI & KOUKOUVELAS (2007) suggest that both landslides occurred before 1945 and reactivated between 1945 and 1969. Two of the studied fans are the result of debris flow of these landslides. The fan of Marathias is developed by the debris flow of Marathias landslide (photo 2) while Vogeri fan is formed by the debris flow of Sergoula slide.

The climate of the study area is temperate Mediterranean. Mean annual precipitation ranges from 800 mm near the coastline to more than 1100 mm in the northernmost highlands. Rain is unevenly distributed during the year with most of it falling during the winter months. Mean annual temperature is about 16 °C. The ephemeral streams are not monitored hydrologically and thus there are no available measurements of water discharge and bedload transport or suspended sediment accumulation. The average mean annual discharge of

Photo 1. The scar of Marathias landslide. The material of this slide has developed the debris flow dominated fan of Marathias.

Photo 2. Coarse material along the channel of Marathias fan.

Photo 3. The typical spoon-like morphology of the Sergoula landslide and the debris flow dominated fan of Vogeri.

the adjacent perennial Mornos River is 40 m^3/sec and the suspended sediment load (prior to regulation due to a dam construction) was estimated to be 0.5-0.8 tons/yr/km^2 (PIPER *et al.*, 1990).

DATA ACQUISITION AND METHODOLOGY

This research is based on quantitative and qualitative data depicting the morphology and morphometry of fans and their catchments derived from field-work and topographical and geological maps at various scales. In order to determine the role of the fluvial sediment supply for the evolution of the fan deltas the correlation between geomorphological features (expressed by morphometric parameters) of the drainage basins and features of their fan deltas was estimated. Drainage networks were delineated from aerial photograph interpretation and topographic maps with a scale of 1:50,000. The same maps, with 20 m contour lines, were used for the measurement of the morphometric parameters of the drainage basins.

A simplified lithological map of the area was constructed from the geological maps of Greece at the scale of 1:50,000 obtained from the Institute of Geology and Mineral Exploration of Greece (I.G.M.E.) (Fig. 2). The lithological units cropping out in the basins area were grouped in three classes: limestones, flysch formations (sandstones, shales and conglomerates) and unconsolidated sediments. The contribution of each one of the three main lithological types to the area of each basin was also estimated.

The identification and delineation of the fans was based upon field observations, aerial photo interpretation and maps of the geology of the area at the scale of 1:50,000 (PARASCHOUDIS, 1977; LOFTUS & TSOFLIAS, 1971). Detailed topographic diagrams at the scale of 1:5.000, with 2 m contour lines, were used for the measurement, estimation and calculation of the morphometric parameters of the fan deltas. All topographic maps were obtained from the Hellenic Military Geographical Service (H.M.G.S). The elevation of the fan apex of the studied fans was measured by altimeter or GPS. Fan deltas morphometric parameters measurement was restricted to the portion of fan sediments above sea-level since the entire fan delta (including the subaqueous part) could not be measured due to the lack of detailed submarine morphology data.

All measurements and calculations of the morphometric parameters were performed using Geographical Information System (GIS) functions. A spatial database derived from detailed analogue maps, geometrically corrected aerial photographs and field work measurements, was constructed utilizing GIS. Data procedure in the analytical context of GIS provided data integration which includes a common geographical reference system, common spatial and temporal coverage, and similar scale and quality of the data. The morphometric variables obtained for each one of the fans and its drainage basin are shown in Table 1.

Self Organizing Maps (SOM) were applied in order to investigate relationships between the parameters of the fans under study and classification tendency. There are a number of training parameters that need to be decided before the training: map size (i.e. the number of map units) and shape, neighbourhood kernel function, neighbourhood radius, learning rate and the length of training. The quality of the SOM obtained is evaluated using two measures as criteria: the quantization error (QE), that is the average distance between each data set data vector and its BMU, and thus, measures map quality and resolution (KOHONEN, 1995). In this study QE value was 0.2, map size was 7x8, the neighbourhood kernel function was Gauss, and learning rate was set to 0.5 neighborhood radious was initially set to 3 and then during finetuning was set to 1.

TABLE 1

Morphometric parameters of the fan deltas and their corresponding drainage basins measured and calculated for this study.

Drainage basin morphometric parameters		
Morphometric Parameter	**Symbol**	**Explanation**
Drainage basin area	(A_b)	The total planimetric area of the basin above the fan apex, measured in km^2.
Basin crest	(C_b)	The maximum elevation of the drainage basin given in m.
Perimeter of the drainage basin drainage basin	(P_b)	The length of the basin border measured in km.
Total length of the channels within the drainage basin	(L_c)	Measured in km.
Total length of 20 m contour lines within the drainage basin	(ΣL_c)	Measured in km.
Basin relief	(R_b)	Corresponds to the vertical difference between the basin crest and fan apex, given in m.
Melton' s ruggedness number	(M)	An index of basin ruggedness (MELTON, 1965, CHURCH & MARK, 1980) calculated by the formula: $M=R_bA_b^{-0.5}$
Drainage basin slope	(S_b)	Obtained using the equation: $S_b=e\Sigma L_c/A_b$ e is the equidistance (20 m for the maps that were used in this study).
Drainage basin circularity	(Cir_b)	It is given by the equation: $Cir_b=4\pi A_b/P_b^2$ and expresses the shape of the basin.
Drainage basin density	(D_b)	The ratio of the total length of the channels to the total area of the basin.
Fan delta morphometric parameters		
Fan area	(A_f)	The total planimetric area of each fan, measured in km^2.
Fan apex	(Ap_f)	The elevation of the apex of the fan in m.
Fan length	(L_f)	The distance between the toe (coastline for most of the fans) and apex of the fan, measured in m.
Fan slope	(S_f)	The mean gradient measured along the axial part of the fan.
Fan concavity	(C_f)	An index of concavity along the fan axis defined as the ratio of a to b, where a is the elevation difference between the fan axis profile and the midpoint of the straight line joining the fan apex and toe, and b is the elevation difference between the fan toe and midpoint.

CLASSIFICATION AND CORRELATION SCHEMES OF THE COASTAL FANS THROUGH SELF ORGANIZING MAPS

Table 2 includes the values of the morhometric variables measured and estimated for the coastal alluvial fans and their catchments (Fig. 3). By far the largest among the coastal alluvial fans in the northern coast of the Gulf of Corinth is that of the Mornos River having an area of 28 km^2. It can be characterized as a delta typically dominated by fluvial supply and wave activity formed by a relatively large river with peren-

TABLE 2
Values of the morphometric parameters for the coastal fans and their drainage basins.

	Stream/fan name	A_b	P_b	L_c	ΣL_c	D_b	S_b	Cir_b	C_b	M	Ap_f	R_b	A_f	L_f	S_f	C_f
1	Varia	27.5	26.5	85.9	592.2	3.13	0.43	0.49	1420	0.26	44	1376	4.2	2.6	0.017	1.10
2	Skala	28.2	25.6	80.6	785.1	2.86	0.56	0.54	1469	0.26	94	1375	4.2	2.9	0.033	1.29
3	Tranorema	30.3	26.4	112.4	798.7	3.70	0.53	0.55	1540	0.26	88	1452	1.6	2.1	0.042	1.05
4	Marathias	2.3	6.8	6.6	52.8	2.87	0.46	0.63	880	0.52	92	788	0.4	0.6	0.157	1.28
5	Sergoula	18.4	19.7	59.7	569.8	3.24	0.62	0.60	1510	0.34	54	1456	0.5	1.2	0.046	1.16
6	Vogeni	2.4	7.9	5.6	63.7	2.34	0.53	0.49	1035	0.53	218	817	0.7	1.3	0.167	1.38
7	Hurous	6.8	11.6	23.2	158.6	3.43	0.47	0.63	1270	0.41	216	1054	2.7	2.8	0.077	1.63
8	Douvias	6.8	10.6	23.6	190.3	3.46	0.56	0.77	1361	0.49	92	1269	0.6	1.6	0.059	1.42
9	Gorgorema	2.5	7.3	6.2	67.7	2.52	0.55	0.59	1060	0.64	48	1012	0.1	0.6	0.082	1.18
10	Aghios Spiridon	1.0	4.4	3.5	32.2	3.39	0.62	0.69	585	0.50	70	515	0.1	0.7	0.095	1.33
11	Linovrocho	3.6	8.6	11.3	86.4	3.09	0.47	0.62	1020	0.49	94	926	0.3	1.2	0.080	1.04
12	Mara	2.1	6.8	7.8	51.4	3.76	0.50	0.57	711	0.45	60	651	0.2	0.8	0.076	1.14
13	Stournarorema	47.1	31.5	142.1	1236.0	3.02	0.53	0.60	1360	0.18	92	1268	4.7	4.5	0.021	1.56
14	Eratini	3.4	8.8	8.6	77.7	2.55	0.46	0.55	1004	0.53	30	974	0.3	0.7	0.044	1.30

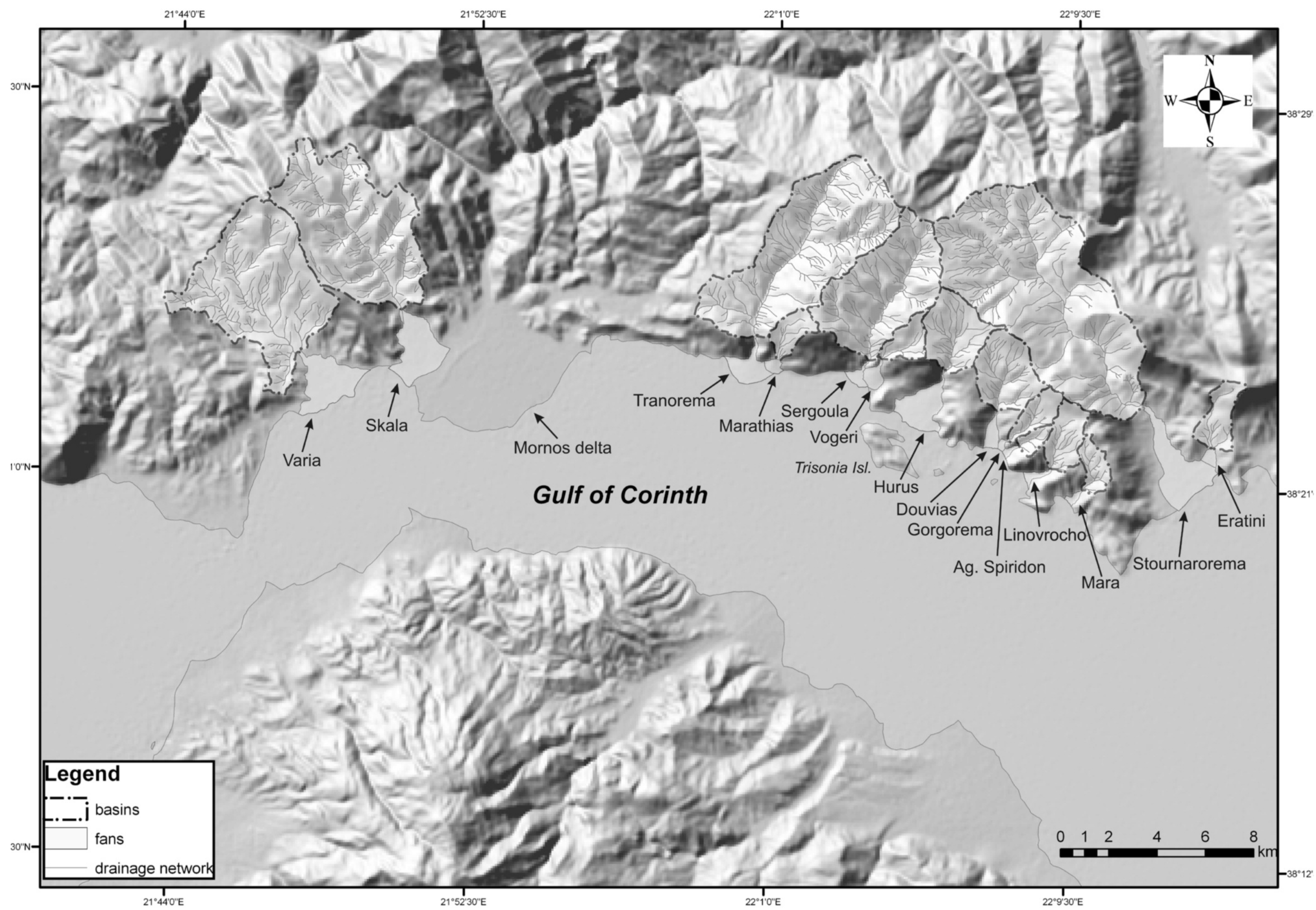

Fig. 3. Topography of the study fans and their drainage basins.

nial flow (Karymbalis *et al.*, 2007). On the contrary the other fans have significantly smaller area ranging between 0.13 and 4.7 km^2 and are associated with streams or torrents of ephemeral flow. This is the reason why the Mornos delta was not included in the data set.

The SOM algorithm was applied in the study as an efficient classification and visualization tool for n- dimensional data set describing alluvial fans along the NW coast of the Gulf of Corinth. One of the problems of visualization of multidimensional information is that the number of properties that need to be visualized is higher than the number of usable visual dimensions. SOM Toolbox (Vesanto, 1999; Vesanto & Alboniemi, 2000) offers a solution to use a number of visualizations linked together so that one can immediately identify the same object from the different visualizations (Buza *et al.*, 1991). When several visualizations are linked together, scanning through them is very efficient because they are interpreted in a similar way.

The U-matrix produced from SOM visualizes distances between neighbouring map units and thus shows the cluster structure of the map. Samples within the same cluster will be the most similar according to the variables considered, while samples very different from each other are expected to be distant in the map.

The visualization of the component planes (n-dimensions of input data set) help to explain the results of the training. Each component plane shows the values of one variable (17 in this study) in each map unit. Simple inspection of the component layers through the multiple visualizations provides an insight to the distribution of the values of the variables. By comparing component planes one can reveal correlations between variables. The examined variables are the morphometric parameters of the alluvial fans and their corresponding drainage basins, analytically presented in Table 2. Two more qualitative parameters were studied: the existence or not of a well developed channel in fan area, and the geological formation that prevails in the basin area. These two parameters were coded and put in the data set, following a binary coding.

The application of the SOM algorithm in the current data set and the result of the classification are presented through

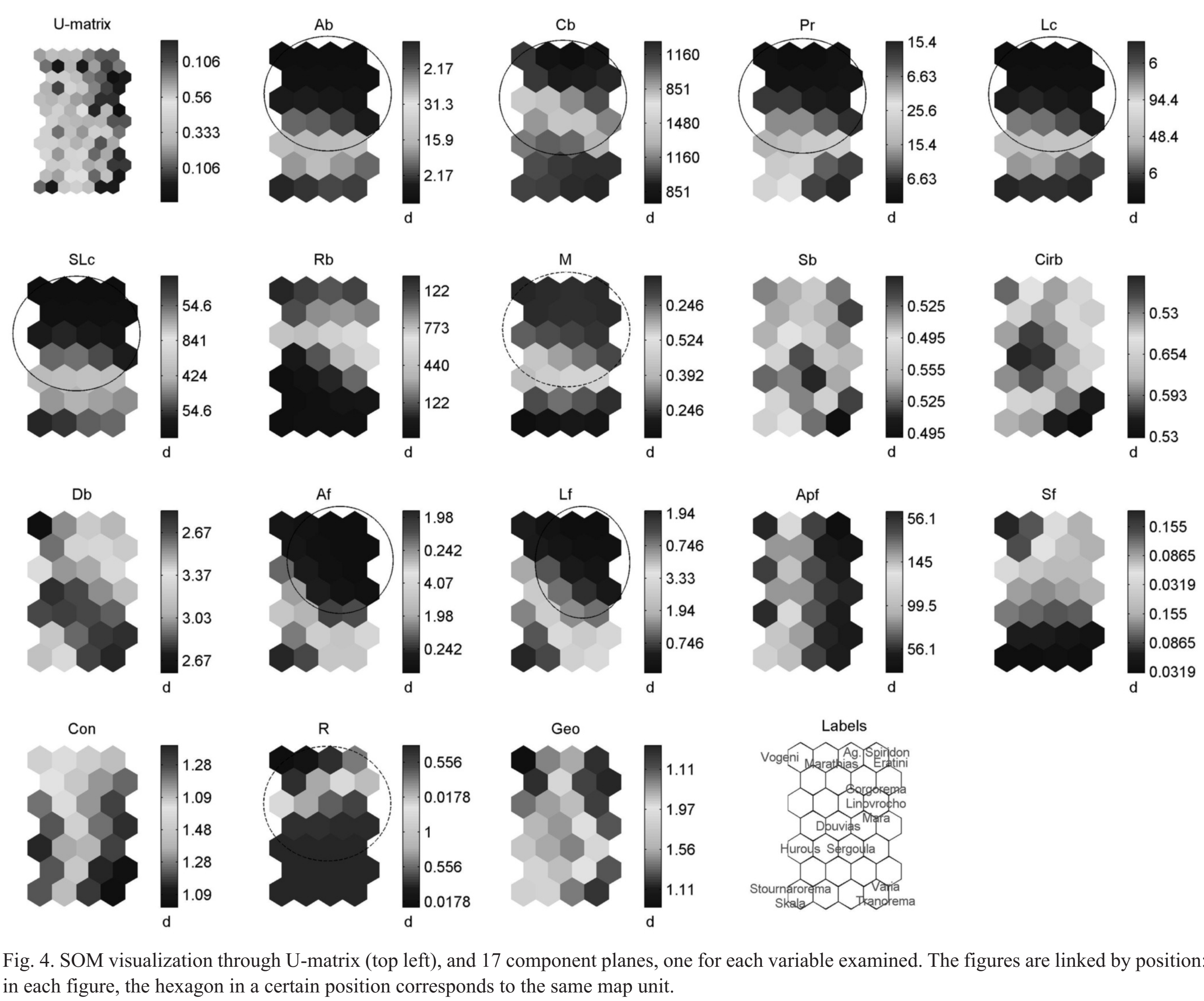

Fig. 4. SOM visualization through U-matrix (top left), and 17 component planes, one for each variable examined. The figures are linked by position: in each figure, the hexagon in a certain position corresponds to the same map unit.

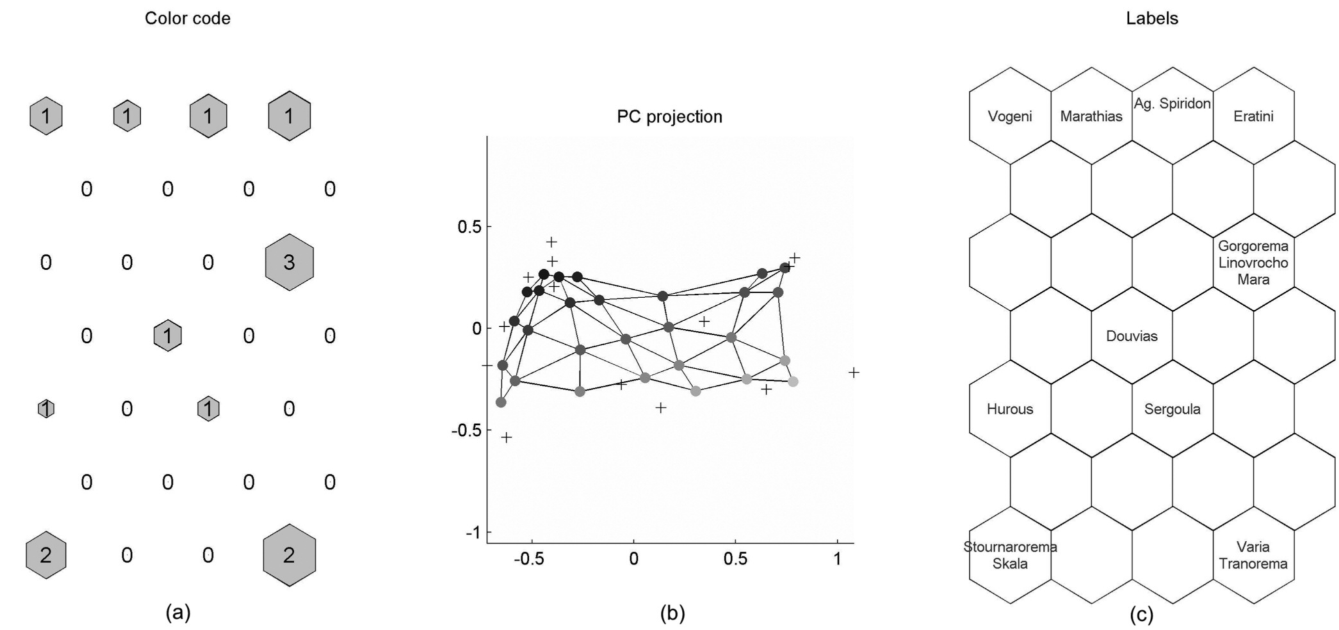

Fig. 5. Different visualizations of the clusters obtained from the classification of the morphological variables through SOM. (a) Colour code; (b) Principal component projection; (c) Label map with the names of the alluvial fans. Clusters are indicated through the circles.

the multiple visualization in Fig 4. It consists of 19 hexagonal grids, the U-matrix upper left along with the 17 component layers and a label map on the lower right. The first map on the upper left gives a general picture of the cluster tendency of the data set. High gray level colors represent the boundaries of the clusters, though low grey level colors represent clusters themselves. In this map 4 clusters are recognized. In Fig. 5 the same visualization is presented through hit numbers in Fig. 5a and the post-it labels in Fig. 5c. The hit numbers in the polygons represent the number of records of the data set that belong to the same neighbourhood (cluster). Through the visual inspection of both Fig. 5 one can correspond the hit numbers to the particular record, which is the alluvial fan name. The records that belong to the same cluster are mapped closer and have the same color. Marathias and Vogeni fans belong to the same cluster. The common characteristics of these two fans are visualized through Fig. 4. Using similarity coloring and position, one can scan through all the parameters and reveal that these two records mapped in the upper corner of each parameter map have always the same values represented by similar color.

Except from general clustering tendency, scanning through parameter layers one can reveal correlation schemes, always following similarity coloring and position. Each parameter map is accompanied with a legend bar that represents the range values of the particular parameter. Drainage basin area (A_b), is correlated with fan area (Ap_f) and fan length (L_f). Total length of channels within basin area (L_c), and total length of contours (ΣL_c) within the drainage basin are also correlated. Basin crest (C_b) and basin relief (R_b) are inversely correlated. Melton's ruggedness number which is basically a slope index for the catchment area, is correlated to both fan slope (S_f) and channel development in fan area. The geological formation prevailing to basin area seems to be inversely correlated to fan concavity. Fan concavity (C_f) is also correlated to fan area.

The SOM classified the data set into four individual clusters in an objective and systematic method. Other algorithms provided by SOM Toolbox (k-means, Principal Component Analysis) were also applied in order to assess the number of clusters (Fig. 5b).

In the following description, the response of the given data to the map (adding hits number) for each cluster of fans was calculated as a cluster index value (CIV). The higher the cluster index value the stronger being the cluster and therefore the most important in the data set and the most representative for the study area.

Fan type 1: Varia, Skala, Sergoula, Stournarorema, Tranorema. The cluster index has the value of 5. Varia and Tranorema form a subgroup. Stournarorema and Scala form another subgroup. This group includes fans formed by streams with well developed drainage networks and large basins with high values of basin relief (Fig. 6). The produced fans are extensive, relatively gently sloping, (with a mean slope of 0.032). Varia, Skala, Sergoula and Stournarorema fans have a triangular shape and resemble small deltas while Tranorema has a more semicircular morphology (Fig. 6). These fans are intersected by well developed and clearly defined distributaries channels consisting of coarse grained material (pebbles, cobles and few boulders). These are generally aggrading fans with an active prograding area near the river mouth. The fans of this group are characterized as fluvial dominated.

Fan type 2: Marathias, Vogeni. The cluster index has the value of 2. This second group involves fans formed by torrents with small drainage basins. They have developed laterally overlaying or confining fans of the cluster 1. Their shape is conical, they do not present well developed channels and are also characterized from high fan gradients (mean fan slope reaches the value of 0.162). Flysch formations prevail in their basin area. According to these features, they seem to be debris flow dominated. Their formation and evolution is inferred to be highly governed by the two landslides of Marathias and Sergoula (Fig. 6, photos 1, 3).

Fan type 3: Gorgorema, Mara, Linovrocho, Ag. Spyridon, Eratini influence. The cluster index is 6. This group includes alluvial fans formed by streams of well developed drainage networks with large basins dominated by the presence of flysch formations (Fig. 2). The fans are elongated and have well developed and clearly defined distributaries channels relatively incised in the most proximal part of the fan, near the apex, which becomes indefinite at the lower part near the coastline (Fig. 6). The slope of their surface (mean gradient of 0.075) is higher than the slope of the cluster 1 fans and lower than those of cluster 2. According to these findings they are characterized as fluvial dominated with debris flow influence.

Fan type 4: Hurus and Douvias. The cluster index is 2. The drainage basins of these two streams have similar features. These two fans are elongated and have well developed distributaries channels, low slope values and high concavity. Their main characteristic is that they have large fan area if compared with the catchment area. They are characterised as fluvial dominated fans. The anomalously large Hurus torrent alluvial fan in relation to its drainage basin area is interpreted to be the result of high sediment accumulation at the mouth of this torrent (Fig. 3). This exceptional accumulation rate is attributed to the reduction of the effectiveness of marine processes due to the presence of Trizonia Island in front of the torrent mouth. This island protects the area of the fan resulting in deposition of the fluvio-torrential material.

The coastal zone at the apron of the coastal fans of all clusters is characterized by the abundance of coarse grained sediments (gravels and pebbles). The large and gently sloping, fluvial dominated, fans have a most irregular coastline with an active prograding area around the river mouth. Although the streams are of seasonal nature, the shoreline of their fans changes very rapidly. For instance Stournarorema fan shows a progradation of about 100 m between 1960 and 1992 (Hasiotis *et al.*, 2006). However from 1992 to 2004 the coastline has retreated about 4 m at the river mouth and about 6 m west of it. The coastline of this fan has suffered earthquake induced instability events. Sediment failures have been certified during the last 40 years (Hasiotis *et al.*, 2002). The coastline of the smaller elongated fans is straight implying that its configuration is the result of marine processes, mainly wave activity and longshore currents.

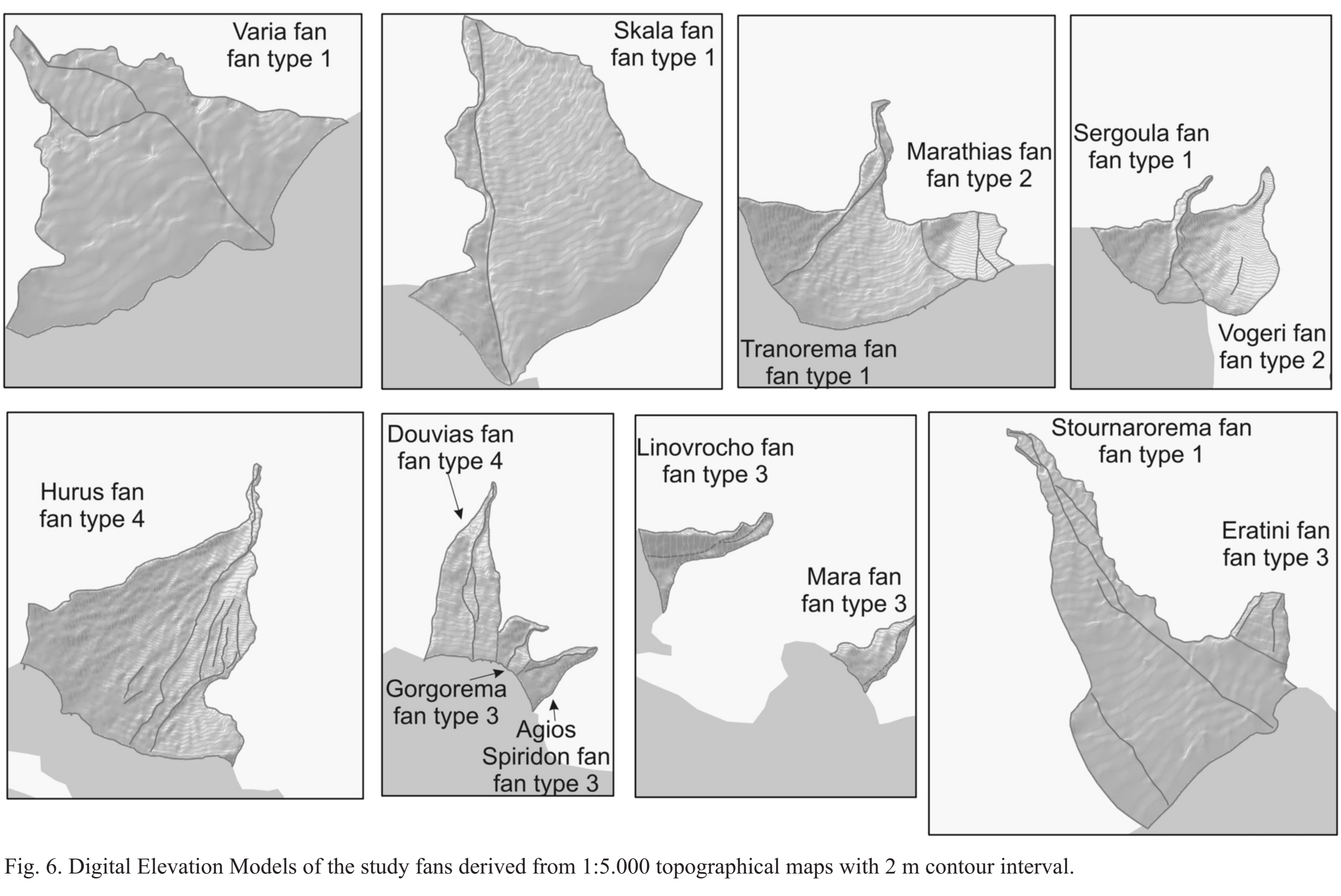

Fig. 6. Digital Elevation Models of the study fans derived from 1:5.000 topographical maps with 2 m contour interval.

FAN - CATCHMENT MORPHOMETRIC RELATIONSHIPS

The study of the morphomety of both alluvial fans and drainage basins reveals much information regarding fan evolution and the dynamics of hydrological processes responsible for fan building. The correlation between the geomorphic features (expressed by morphometric parameters) of the studied fans and their drainage basins include the investigation of the relationships between drainage basin area and fan delta area, drainage basin area and fan delta slope and fan delta slope and Melton's ruggedness number.

Drainage Area (A_b) versus Fan Area (A_f)

An established way to describe the relationship between fans and drainage basins is to relate their respective areas. BULL (1962) was the first to describe this relation quantitatively and recognized that as drainage basin area increases, the size of the alluvial fan also increases. He quantified the relationship with a simple power function of the form:

$$A_f = cA_b^k$$

where Af is alluvial fan area, Ad is drainage basin area and c is an empirical derived coefficient representing the area of an alluvial fan with a drainage basin area of 1.0. The exponent k is the slope of the regression line and measures the rate of change in fan area with increasing drainage basin area. OGUCHI & OHMORI (1994) showed that Bull's equation represents the coupling of three functional relationships between basin area and basin slope, basin slope and sediment yield and sediment yield and fan area. Comparison of these two parameters offers the most interesting correlation for the coastal fans of the study area. By representing this relation on a log - log plot (Fig. 7a) becomes clear that the data fit a single exponential function:

$$A_f = 0.13A_b^{0.88}$$

with a high correlation coefficient of 0.83. The reason for this strong positive relation is that sediment discharge out of the catchment increases as drainage area increases.

The coefficient, which according to HARVEY (1997) typically ranges from 0.1 to 2.2, has the value of 0.13 for the study area. The exponent attains the value 0.88 and is in agreement with the aspect that the exponent varies from 0.7 to 1.1 (HARVEY, 1997) and that it is generally less than 1.0 (HOOKE & ROHRER, 1977). In the literature different values of the exponent k and the coefficient c for humid and subhumid region fans have been reported (CROSTA & FRATTINI, 2004). This variability has been attributed to different factors, such as climate conditions, tectonic setting, and relative erodibility of source area rock types. Table 4 includes values of coefficient c and exponent k in the power law relationship between drainage area and fan area from research works in various morphoclimatic environments. The value of the exponent for the study area agrees with the typical value for arid regions (about 0.9) (HOOKE, 1968) and 0.88 (OGUCHI & OHMORI, 1994) and is higher than those derived from humid (0.58) and polar (0.65) regions. This value shows that the fans increase little in extension when the drainage area increases. The lower than 1.0 value implies that larger basins supply proportionately less sediment to alluvial fans than smaller basins. This might happen because larger alluvial fans may take longer to adjust to the available space and achieve equilibrium than smaller fans. This has been attributed to the shorter distances that sediment has to travel to reach the smaller alluvial fans. The negative allometric relationship, which means that fan area does not increase as quickly as the contributing drainage basin area, has been attributed to the fact that larger basins can store sediments in tributaries and on valley slopes, reducing the sediment supply to alluvial fans (HOOKE, 1968). For fluvially dominated

TABLE 3

Participation (in km^2 and %) of each one of the three main lithological groups for the drainage basins. U.S, L and F stand for unconsolidated sediment, limestones, and flysch respectively.

	Basin name	km^2			% of the total basin area		
		U.S.	L.	F.	U.S.	L.	F.
1	Varia		9.0	18.5		32.8	67.2
2	Skala	0.7	25.6	2.0	2.4	90.6	7.0
3	Tranorema	0.2	8.2	21.9	0.8	27.1	72.1
4	Marathias		1.6	0.7		70.6	29.4
5	Sergoula		12.1	6.4		65.5	34.5
6	Vogeni		1.4	1.0		57.6	42.4
7	Hurous		0.8	5.9		12.2	87.8
8	Douvias		4.1	2.7		60.1	39.9
9	Gorgorema	0.4	0.5	1.6	16.9	19.6	63.5
10	Aghios Spiridon		0.1	0.9		11.5	88.5
11	Linovrocho	0.5	0.4	2.7	14.1	10.8	75.2
12	Mara		1.0	1.1		46.2	53.8
13	Stournarorema	0.3	18.5	28.3	0.7	39.2	60.1
14	Eratini		1.6	1.7		48.4	51.6

TABLE 4

Values of coefficient c and exponent k in the power law relationship ($Af=cAb^k$) between drainage area and fan area from previous research works performed in various environments.

Location	c	k	Reference
Dellwood, North Carolina, USA	0.23	0.53	MILLS (1982)
Roan Mountain, North Carolina, USA	0.38	0.76	MILLS (1983)
General River Valley, Costa Rica	0.92	1.01	KESEL (1985)
Banff, Alberta, Canada, fluvial fans	0.48	0.32	KOSTASCHUK *et al.* (1986)
debris-flow fans	0.17	0.48	KOSTASCHUK *et al.* (1986)
single group of fans	0.15	0.77	GILES (2010)
Japan	2.23	0.40	OGUCHI & OHMORI (1994)
Central Alps, Northern Italy	0.29	0.33	CROSTA & FRATTINI (2004)

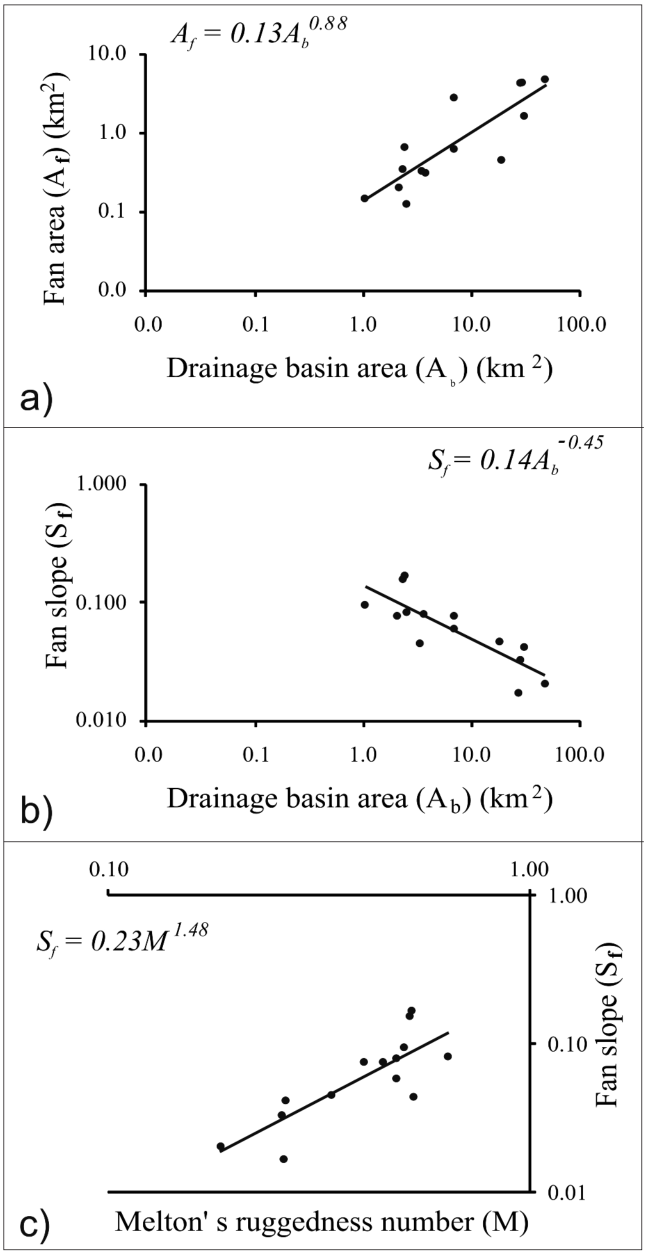

Fig. 7: a) Drainage basin area (A_b) vs. fan area (A_f), b) drainage basin area (A_b) vs. fan slope (S_f) and c) Melton's ruggedness number (M) vs. fan slope (S_f) log-log plots plots.

fans, larger basins may yield a sufficient water discharge to transport a greater portion of sediment across the fan rather than depositing it. In contrast, for debris flow fans (like those of Marathias and Vogeri) smaller basins are usually steeper, thus producing flows with lower strength and proportionally larger surface area than larger gentler basins.

A relatively anomalous relationship for A_b vs. A_f is observed for Hurus river. The size of this fan is much larger than the trend line would predict for a catchment of the given size. This is attributed to the presence of Trizonia island in front of the river mouth, that eliminates wave activity enhancing the deposition of riverine sediments along the coastline.

Drainage Area (A_b) versus Fan Slope (S_f)

Another relationship that has been investigated in the literature is the one between the drainage basin area (A_b) and the fan gradient (S_f) (HOOKE, 1968; HARVEY *et al.*, 1999). This relation is also quantified with a simple power function of the form:

$$S_f=cA_b^k$$

Although the correlation coefficient (-0.68) is negative and lower than that for the previous couple of parameters this relation for the studied fans (Fig. 7b) can also fit the following function:

$$S_f=0.14A_b^{-0.45}$$

The value of the exponent (-0.45) falls within the range of values (-0.35 to 0.15) determined for the majority of examples described by other authors (HARVEY, 1997) while the coefficient (0.14) is also within the range of previously reported values (0.03 to 0.17) . The reason for this correlation is that water discharge increases with drainage area resulting in higher flow velocities and bed shear stress. Thus the flow is capable of transporting on a lower slope the same material transported by smaller discharges on a higher slope.

Fan Slope (S_f) versus Melton's Ruggedness Number (M)

Melton's ruggedness number is a dimensionless measure of basin relative relief which incorporates measures of travel distance and available relief in the basin, thus providing an effective measure of the gradient with which material moves down, toward the fan (CHURCH & MARK, 1980; KOSTASCHUK *et al.*, 1986). A valuable characteristic of the Melton' s ruggedness number is its capability of discriminating basins with debris flow potential from basins where sediment transport processes are dominated by bedload (MARCHI & DALLA FONTANA, 2005). The relation between fan gradient (S_f) and Melton's ruggedness number (M) can be quantified with a power function of the following form:

$$S_f=cM^b$$

The correlation coefficient for this pair of parameters for the fans of the study area is relatively high and positive (0.67). A plot of basin Melton's ruggedness number against fan gradient for all fans is illustrated in Fig. 7c. The power function that describes the relation is:

$$S_f=0.23M^{1.48}$$

The values of b from early previous studies approximate 1.00 and CHURCH & MARK (1980) postulate that a general linear relation exists for S_f versus M. For the study area value of b (1.48) exceeds 1.00 indicating that the fan slope is increasing more rapidly than the ruggedness of the basin.

According to De Scally & Owens (2004) debris-flow fans are supplied by basins with a higher Melton's ruggedness number while the fans are steeper, smaller and less concave. The differentiation of debris flow and normal fluvial processes is important because of the much greater erosive and destructive potential of the former (Descally & Owens, 2004). This relationship provides an initial assessment of debris-flow potential for the broader study area, but this needs to be supported by field investigation of debris flows and sediment supply conditions in the basin. The two verified debris flow dominated fans (Marathias and Vogeri fans) are those represented in the diagram of Fig. 7 by high values of both Melton's number and fan slope. Debris flow potential assessment is important since the area is susceptible to mass movements triggered by earthquakes. The study area is prone to landslides due to the presence of preexisting structure of the contact of the cherts with the limestones which represent a strong mechanical boundary within the litholstratigraphic column of the Pindos geotectonic zone (Gallousi & Koukouvelas, 2007). Much of the westward movement of the rocks in the Pindos zone is taken up by ramps located within this contact (Xypolias & Doutsos, 2000). A series of landslides are recognized adjacent to the Marathias fault or parallel to the thrust planes of the Pindos zone, where they appear to be controlled by the intersection of the two structures.

CONCLUSIONS

This research is a contribution to the identification of fourteen coastal alluvial fans which are the main geomorphological characteristic of the northwestern coast of Gulf of Corinth. The configuration of these landforms is the result of the combination of suitable conditions for fan delta formation during the Late Holocene. Highly erodible lithology (more than 60% of the basins consist of flysch formations) and steep slopes have enhanced erosion over the drainage basins. Intensive weathering over the catchment areas has resulted in large quantities of weathered coarse grained sediments readily available for transportation. In addition the extremely low tidal range and Late Holocene sea-level rise stabilization have permitted sediment accumulation in the area of the stream mouths.

Qualitative observations in addition to quantitative geomorphological analysis and the application of Self Organizing Maps led to the definition of four main types of fans with different morphological features and the identification of certain correlation schemes between the studied parameters. Large stream basins have produced relatively extensive gently sloping fans dominated by fluvial processes while torrents with small rough drainage basins have formed steep debris-flow dominated fans. Two of the studied fans have developed by debris flow due to earthquake triggered landslides and allowed us to determine the threshold morphometric values between the debris flow dominated and the fluvial dominated fans for the study area. Fluvial dominated fans present a shifting coastline especially at the vicinity of the river mouths. Fan morphometric variables were related to the drainage basin geomorphological characteristics. Power functions describing empirical relationships are in agreement with similar data published for arid regions around the world. A strong positive relationship between fan area and drainage basin area was established, through simple power functions and Self Organising Maps. The exponential function for the fan area - basin area relation showed that larger basins supply proportionally less sediment to coastal fans than the smaller ones. An anomalous basin area - fan area relationship was observed for Hurus river which is attributed to the exceptional high coarse grained sediment accumulation at the mouth of the river. Trizonia Island is located in front of the river mouth protecting the shoreline from wave action that removes sediment.

The positive relationship of fan gradient and Melton's ruggedness number was also discovered through Self Organising Maps. This relationship provides an initial assessment of debris-flow potential within the studied basins. However, this needs to be supported by more detailed field investigation of debris flows and sediment supply conditions in the basin as well as by sedimentological observations of the fans deposits.

The systematic and objective method of unsupervised artificial neural networks which was applied in the field of alluvial fan classification gave reasonable results, compared to statistical methods, and expert geomorphologists' observations. This method could be applied as a generic tool to classify larger data sets of alluvial fans, in order to assess and interpret dominant formation processes, through the study of various morphometric features describing alluvial fans and corresponding drainage basins.

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APPENDIX
SOM Training procedure

The SOM is trained iteratively. In each training step a sample vector x from the input data set is chosen randomly and the distance between x and all the weight vectors of the SOM, is calculated by using an Euclidean distance measure. The neuron with the weight vector, which is closest to the input vector x, is called the Best Matching Unit (BMU). The distance between x and weight vectors is computed using the following equation:

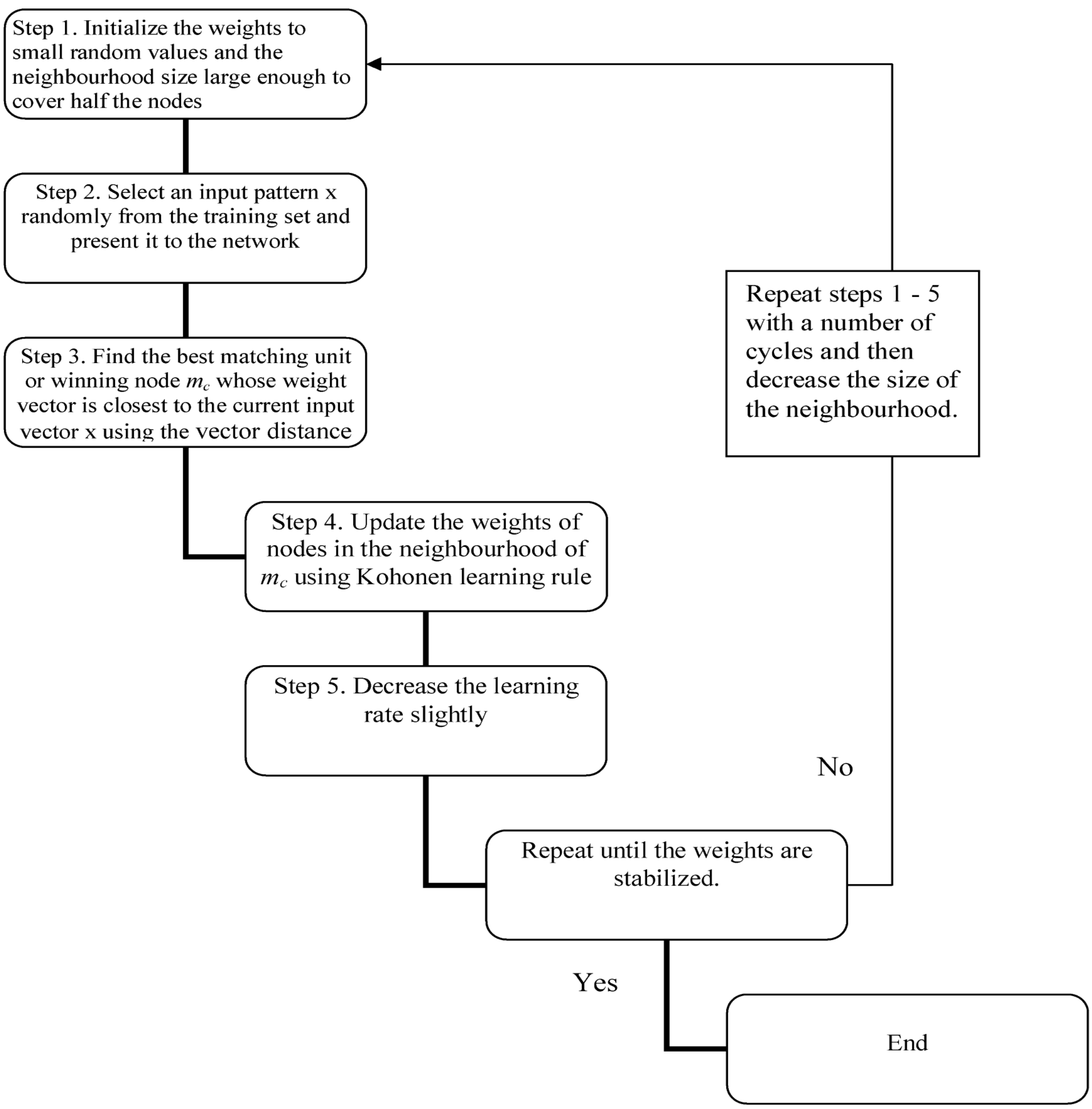
$$\| x - m_c \| = \min\{\| x_i - m_i \|\} \quad (1)$$

where ||.|| is the distance measure, typically Euclidean distance. After finding the BMU, the weight vectors of the SOM are updated so that the BMU is moved closer to the input vector in the input space. The topological neighbors of the BMU are treated similarly. The update rule for the weight vector of i is

$$x_i\,(t+1) = m_i\,(t) + \alpha(t)h_{ci}(t)[x(t) - m_i(t)] \quad (2)$$

where x(t) is an input vector which is randomly drawn from the input data set, a(t) function is the learning rate and t denotes time. A Gaussian function $h_{ci}(t)$ is the neighborhood kernel around the winner unit mc, and a decreasing function of the distance between the i^{th} and c^{th} nodes on the map grid. This regression is usually reiterated over the available samples. The dataset of manufacturing details are fed into the input layer of SOM.

In the following scheme SOM training procedure is presented



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