



Variation in canyon morphology and their relationship with tectonic: the example of the western Algerian margin

Lounes Fernane¹ · Rachid Matougui² · Nadia Amarni¹ · Rabah Belkessa¹

Received: 13 July 2021 / Accepted: 19 January 2022 / Published online: 26 January 2022
© Saudi Society for Geosciences 2022

Abstract

The Algerian margin is a passive margin located in the south of the western Mediterranean that developed as a back-arc basin behind the subduction of the Tethyan Ocean underneath the African plate during the Miocene. Presently in compression, it is one of the most seismically active areas in the Western Mediterranean, having experienced several moderate to strong earthquakes in the coastal zone during the last century. The morphology of the continental slope offshore Algeria is steep and dominated by the presence of numerous canyons of variable size and sea-floor escarpments that are probably the expression of active thrust-folds. As a result, the morphology of the canyon reflects the interplay between tectonic deformation and canyon evolution. The main objective of this paper is to make a morphometric analysis of the submarine canyons of the Algerian western margin, to discern their possible origin as well as to discuss their evolution, using high-resolution bathymetric data acquired during the MARADJA 1 cruise in 2003. From the morphometric analysis, it can be seen that where the continental shelf is narrow or even non-existent canyons are very incised, dendritic and ramified, highly developed, and apparently very active, whose origin may be associated with sub-aerial drainage systems. These canyons are most likely maintained by gravity flows during the marine transgression, and have concave longitudinal depth profiles suggesting a mature stage of their evolution. In areas where the continental shelf is wide, canyons are confined to the continental slope and are disconnected from a sub-aerial river system. They are less incised, less ramified, and poorly developed. The origin of the slope-confined canyons is rather controlled by retrogressive erosion and small landslides. These canyons have convex longitudinal depth profiles, suggesting a juvenile stage of their evolution. Finally, we suggest that the submarine canyons on the Algerian margin are affected by compressive tectonics, which accentuate eastward of the margin.

Keywords Western Algerian Margin · Submarine canyons · Morphometric analysis · Retrogressive erosion · Compressive tectonics

Responsible Editor: François Roure

✉ Lounes Fernane
lounes15@live.fr
Rachid Matougui
rmatougui@hotmail.com
Nadia Amarni
amarninadia@hotmail.com
Rabah Belkessa
belkessarabah@yahoo.fr

¹ Marine and Coastal Ecosystems Laboratory, Higher National School of Marine Sciences and Coastal Management. Dely Ibrahim, Bois Des Cars University Campus, 16320 Algiers, Algeria

² Geo-Environment Laboratory, Faculty of Earth Sciences, Geography and Land Management, Houari Boumedienne University, BP. 32, El-Alia-Algiers, Algeria

Introduction

Submarine canyons are geomorphic features encountered on any type of continental margin (Harris and Whiteway 2011) and are the preferred pathways for the transfer of sediments from the continental shelf to the deep basin through submarine landslides and turbidity currents (Nittrouer and Wright 1994; Babonneau et al. 2002; McHugh et al. 2002; Normark et al. 2003).

Submarine canyons are defined as “steep-walled, sinuous valleys with V-shaped cross-sections, axes sloping outward as continuously as river-cut land canyons and relief comparable to even the largest of land canyons” (Shepard 1963).

Since their discovery in the nineteenth century, various hypotheses have been proposed to explain how submarine canyons formed:

- Fluvial erosion during the decrease sea level: a morphological link has been established between submarine canyons and river systems. In 1903, Spencer hypothesized that these features corresponded to ancient river beds submerged at the end of the Pleistocene glaciations. This hypothesis could explain the formation of some of the Messinian canyons in the Mediterranean Sea (Shepard 1981).
- Several studies have evidenced their initiation by upslope retrogressive erosion (Twichell and Roberts 1982; Farre et al. 1983; Pratson and Coakley 1996) and downslope incision by gravity-flow processes (Daly 1936; Pratson et al. 1994; Pratson and Coakley 1996; Mulder et al. 1997).
- Hyperpycnal currents are generated during high floods at river mouths (Daly 1936; Shepard 1981; Twichell and Roberts 1982; Farre et al. 1983; Pratson and Coakley 1996; Krastel et al. 2001; Baztan et al. 2005). The continuous input of particulate matter via the direct connection of the river to the canyon head maintains the incision/filling phenomena of underwater canyons or axial incision phenomena (Baztan et al. 2005).
- Tectonics can also influence the course of some canyons, with the canyon thalweg being deflected along faults and structural features (Mountjoy et al. 2009; Harris and Whiteway 2011).
- Orange et al. (1994), Orange and Breen (1992) have attributed the origins of some blind canyons (Harris and Whiteway 2011) to fluid seepage-induced slope failure.
- Furthermore, the investigations on submarine cable breaks following the 1929 Grand Banks earthquake demonstrated erosive power of turbidity currents and their implications in the formation of canyons (Heezen and Ewing 1952; Heezen et al. 1954). More recently, Puig et al. (2014) have identified six major triggering mechanisms of contemporary sediment transport after high frequency, long-term in situ monitoring data. These processes are storm-induced turbidity currents and enhanced off-shelf advection, hyperpycnal flows and failures of recently deposited fluvial sediments, dense shelf water cascading, canyon flank failures and large submarine slope failures, and trawling-induced re-suspension. Additionally, internal waves can also contribute to the re-suspension of ephemeral deposits within canyons.

Three main types of submarine canyons are distinguished depending on the canyon head configuration on the continental margin and its potential connection to nearby rivers (Harris and Whiteway 2011):

Type I: Canyon incising the continental shelf and connected with a river mouth (Babonneau et al. 2002;

Greene et al. 2002; Michels et al. 2003; Cronin et al. 2005; Antobreh and Krastel 2006; Harris and Whiteway 2011);

Type II: Canyon incising the continental shelf but without a direct connection with a river (Twichell and Roberts 1982; Zaragosi et al. 2001; Berné et al. 2002; Hill and Cota 2005; Arzola et al. 2008; Green 2011; Harris and Whiteway 2011) and;

Type III: Canyon confined to the continental slope (O'connell et al. 1987; Bertoni and Cartwright 2005; Green et al. 2007; Green 2011; Harris and Whiteway 2011; Jobe et al. 2011).

These main types of canyons can also be divided according to their maturity degree (Twichell and Roberts 1982; Farre et al. 1983; Goff 2001), from “mature” canyons (Twichell et al. 1977; Mitchell 2005; Gaudin et al. 2006); to “juvenile” canyons (Twichell and Roberts 1982; Pratson and Coakley 1996; Goff 2001; Mitchell 2005; Antobreh and Krastel 2006). Mature canyons are generally large, isolated (Allen and Madron 2009), dendritic in their head and meandering downslope (Farre et al. 1983; Pratson and Coakley 1996; Popescu et al. 2004; Harris and Whiteway 2011). They are deeply incised into the continental shelf and present a direct connection with their sub-aerial feeding system (Babonneau et al. 2002; Greene et al. 2002; Cronin et al. 2005; Antobreh and Krastel 2006; Gaudin et al. 2006; Harris and Whiteway 2011). These canyons generally present a concave longitudinal depth profile with a slope gradient decreasing downslope (Goff 2001; Mitchell 2005; Covault et al. 2011). Juvenile canyons are smaller and straighter (Mitchell 2005) and less dendritic (Bertoni and Cartwright 2005; Harris and Whiteway 2011), and show confined-slope heads (O'connell et al. 1987; Miller and Mountain 1996; Orange et al. 1997; Bertoni and Cartwright 2005; Cronin et al. 2005; Green et al. 2007; Green 2011). These canyons are starved from any sedimentary supply from the continental shelf, involving slope erosional processes (Harris and Whiteway 2011). Slope-confined canyons generally present a convex or sigmoid longitudinal depth profile (Goff 2001; Covault et al. 2011).

Furthermore, three main trends of canyon longitudinal depth profiles are distinguished: concave, linear, and convex (Covault et al. 2011). Each trend may correspond to a continental margin type (passive or active), because longitudinal profile generally reflects the influence of tectonic factor (uplift/subsidence) and sedimentary processes deposition/erosion (Covault et al. 2011).

Therefore, concave or exponential trend may be associated with steep and active margin with a narrow continental shelf and a close hinterland (Goff 2001); the margin presents a high erosion rate (Covault et al. 2011).

A linear trend usually characterizes mature passive margins that are dominated by fluvial supply, and subject to a thermal subsidence (Covault et al. 2011).

Finally, convex trend or sigmoid may be the result of tectonic uplift and deep-basin deformation (Goff 2001). They are generally associated with passive margins affected by active tectonic convergence (Covault et al. 2011).

This study is focused on the submarine canyons located along the western margin of the Algerian basin. This margin segment formed during the Miocene, in a back-arc basin context of the Tethyan subduction, with a plunging plate tear, which gave rise to a continental margin in STEP (Subduction-Transform Edge Propagator) (Govers et Wortel 2005; Badji et al. 2014; Medaouri et al. 2014).

The main objectives of this work are:

- To describe the main morphological characteristics of the canyons, such as width, depth, valley morphology, longitudinal depth profile, and projected upstream/downstream evolution,

- To establish the origin of submarine canyons and their control factors,
- To identify clues that could reflect the compression of this margin.

General framework

Geological framework

Northern Algeria is mainly composed of rocks that were influenced by the Maghrebien orogeny (Frizon de Lamotte et al. 2000; Bracene 2002; Domzig et al. 2006), which can be described from south to north by (Fig. 1):

- (1) The Atlasic domain consists of Jurassic carbonates overlain by Cretaceous to Tertiary shales, sands, and carbonates.
- (2) The external domain, also called the Tellian units, with folds and thrusts verging to the south, and composed of sedimentary rocks (mainly marls and limestones);

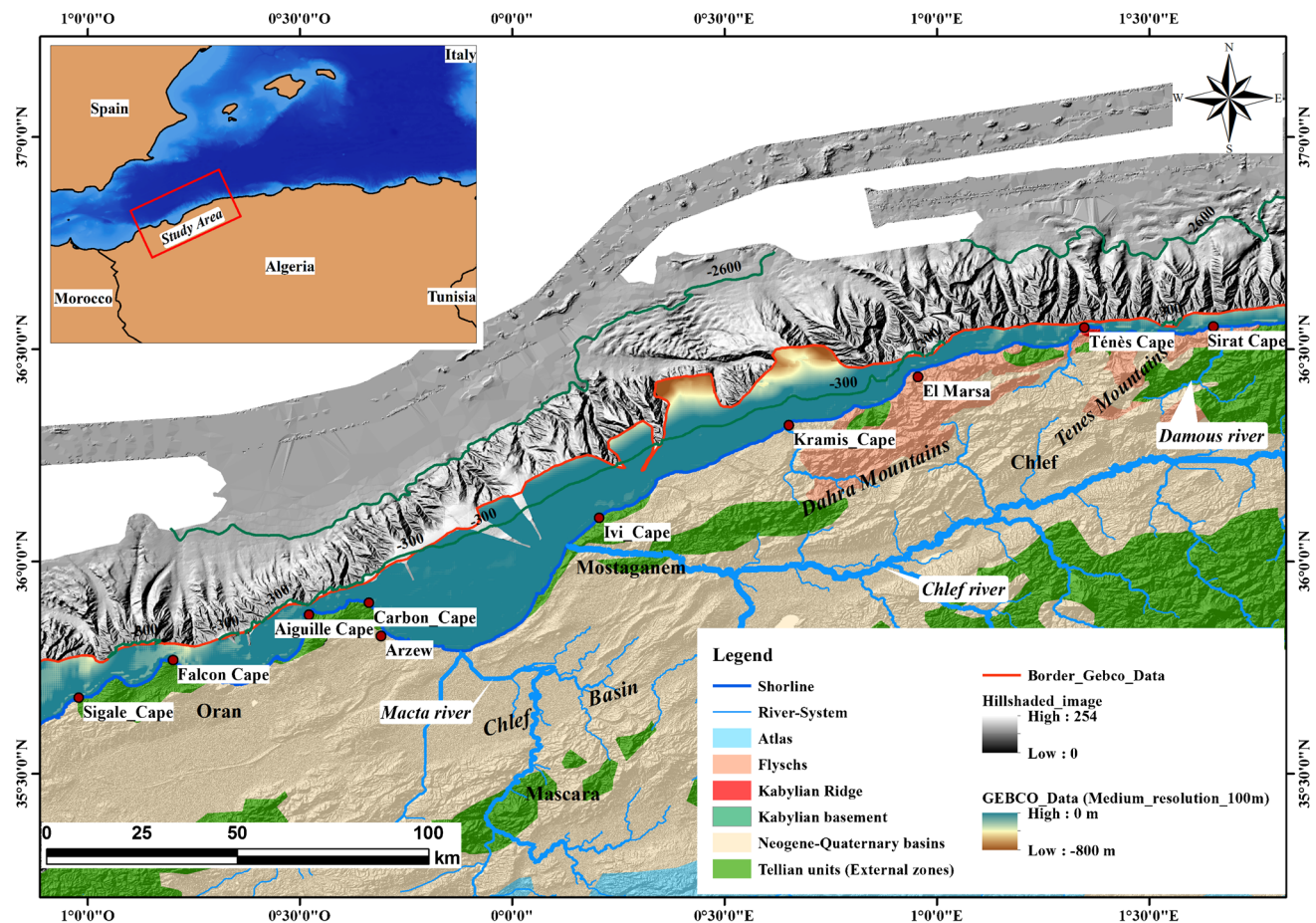


Fig. 1 Map of the study area presents the geology of the western Algerian margin, and the bathymetric data sets which are used to map the submarine canyons

(3) The flyschs units correspond to upper Jurassic, Cretaceous, and Tertiary sediments deposited south of the AlKaPeCa domain (standing for Alborán, Kabylia, Peloritana, and Calabria), in the Tethyan Ocean. They consist of turbiditic sedimentary sequences (sands and shales).

(4) The Internal domain, composed of hard Hercynian basement rocks, sometimes associated with its sedimentary cover, the “Dorsale Kabyle,” which is a relict of the AlKaPeCa domain (Bouillin et al. 1986).

The sedimentary cover of the Algerian offshore is described in several works (Auzende 1978; Domzig et al. 2006; El-Robrini 1986; Hsü et al. 1973; Medaouri et al. 2012, 2014). A remarkable feature of this cover is the existence of the salt series of Messinian age (Upper Miocene), deposited in the basin areas as a result of the Messinian Salinity Crisis, between 5.96 and 5.32 Ma (Clauzon 1982; Rouchy et al. 2001).

This Messinian Salinity Crisis materialized in a large drop in sea level, which corresponds to one or more phases of drying up of the Mediterranean, which led to a strong erosion of the margin, and to the deposition of large quantities of evaporites in the basin (Gargani and Rigollet 2007). After the Pliocene reflooding, the Pliocene to Quaternary sediments were deposited. These saliferous deposits have a mechanical property that favors syn-sedimentary mobility and diapirism phenomena (Domzig et al. 2006).

Margin physiography

The Algerian margin in North Africa is part of the Western Mediterranean domain. The study area is located along the western margin of Algeria, at the transition between the transform margin of the Alboran Sea to the west and the passive margin of the Algerian basin to the east, which extends from Sirat cape to Sigale cape over about 300 km (Fig. 1). The western Algerian margin has an ENE-WSW orientation, while the rest of the margin is generally E-W oriented.

In terms of orography, the study area is bordered by the Ténès and Dahra Mountains extending between Ténès and Mostaganem (Fig. 1) where the topography is relatively abrupt, the altitudes are variable from 1000 to 1500 m.

The western Algerian margin is one of the steepest margins in the western Mediterranean (Leclaire 1972). It is characterized by a very narrow continental shelf, especially in front of the high massifs (Ténès and Dahra) (Domzig et al. 2006; Matougui 2008) (Fig. 1).

In its Eastern part, off Ténès, the Algerian margin is characterized by a narrow continental shelf (2–5 km wide); it is almost non-existent off the town of Ténès (Fig. 2a), but the shelf edge lying at 50–100 m water depth is located close to the coastline. The continental slope extends to water depths

of 2500–2600 m, over a width of 25 km, with an average gradient of 8–10°.

The continental slope is excavated by numerous submarine canyons. Most canyons are NW–SE oriented, straight, and narrow, with sharp ridges, each of canyons being fed by several gullies and secondary tributaries. The base of the continental slope is characterized by an abrupt break-in-slope, reaching values $\leq 2^\circ$. There is also a submarine dune field (Deep-Sea-Fan Kramis) at the mouth of the Kramis canyon, at a depth of 2500 m (Domzig et al. 2006; Matougui 2008).

On the other hand, faced with the Neogene basins, such as the Chélif basin, the continental shelf becomes wider (up 30 km) (Fig. 2b). The shelf-edge is located between 100 and 200 m water depths, far from the coast (up 33 km). Conversely, the continental slope becomes narrow (less than 15 km) with an average slope gradient of 12–14°. In the deep basin, beyond 2600 m depth, the gradient is less than 1°.

Climatic and hydrological background

Algeria is characterized by a hot and arid climate; only the coastal zone is characterized by a Mediterranean climate. The configuration of the coastal reliefs plays an important role on the meteorological conditions, more particularly on the pluvial regime.

The rain is generally irregular, sometimes very violent and unevenly distributed. According to an established average, based on data from the National Meteorological Office (ONM) (1986–1994 period), the coastal regions receive an annual rainfall of about 690 mm/year.

The drainage system on land is rather seldom. The largest watershed in the study area is the Chlef watershed. It is 300 km long, has an average slope gradient of 1 to 2°, and drains a basin of 26,750 km².

Valley Chlef originates from the Tellian Atlas and diversifies in front of the large Arzew Bay; it is the main source zone of sediment in the region (Fig. 1).

However, in the east, the size of the watersheds decreases sharply to 200 km², while the average slope increases by 4 to 5°. These watersheds characterized by small valleys, often have episodic torrential behavior. During flash floods, hyperpycnal currents might be generated.

Data and methods

The data set used in this study was acquired during the MAR-ADJA 1 oceanographic survey in September 2003 (MAR-ADJA: MARge Active el DJazaïr, el Djazaïr = Algiers) on board the Suroît research vessel (IFREMER). The bathymetric and reflectivity data along the slope were obtained using a Kongsberg EM300 Simrad multibeam echosounder,

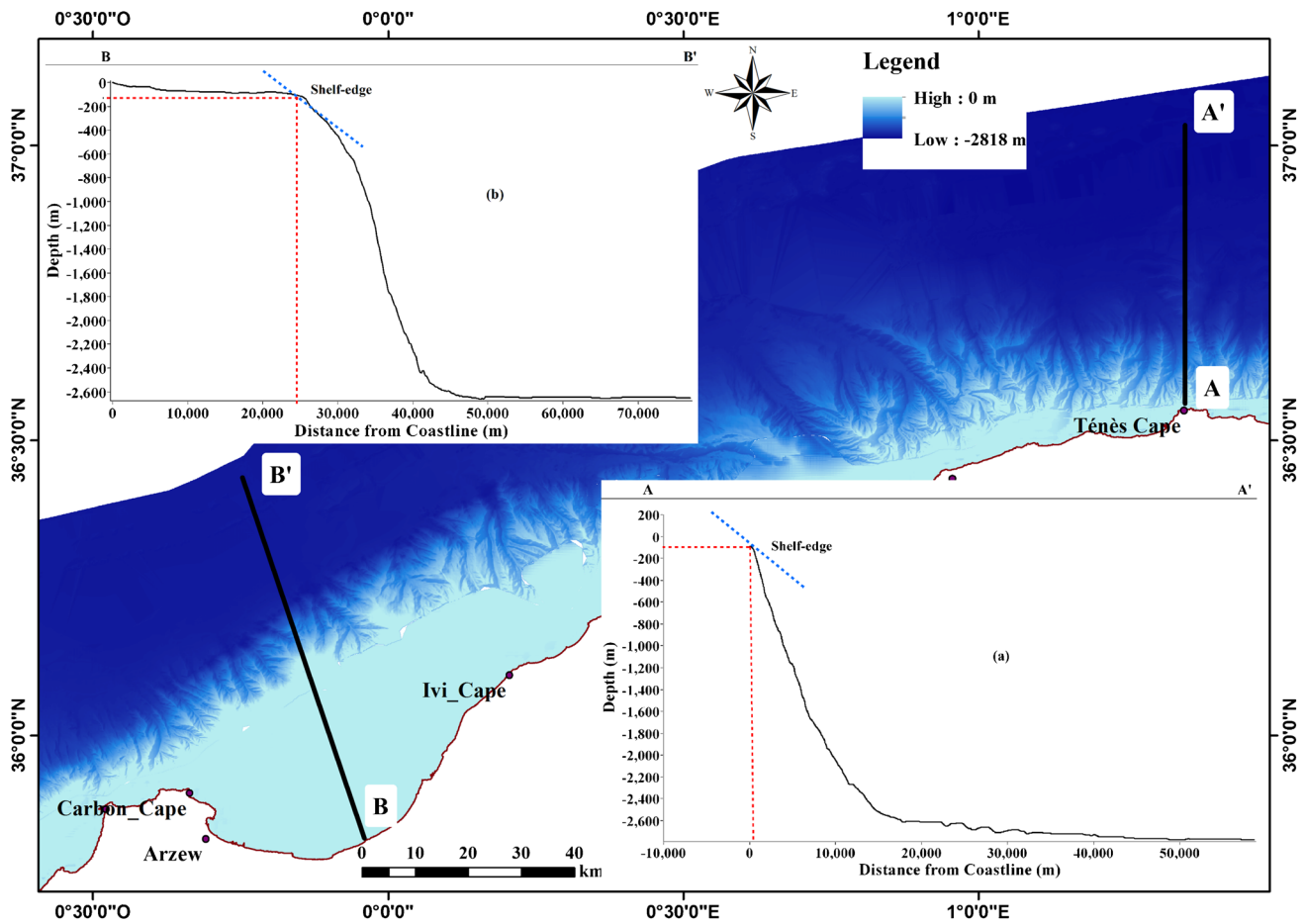


Fig. 2 Map showing the continental shelf extent; **a** longitudinal depth profile shows a narrow continental shelf located in Ténès cape; **b** longitudinal depth profile shows a wide continental shelf located in front of the Chélif basin

whereas a Kongsberg EM1000 was used for acquiring data along the continental platform. Simrad EM300 is a 32-kHz multibeam system that allows for overall swath coverage of ~6 times the water depth, increasing with depth to a maximum width of 5000 m at 1000 m. Its vertical accuracy can reach 2 m for the central beam and its lateral resolution is at most ~25 m. The bathymetric information allows for a precise study of the morphology of the seabed, and the backscatter data allows for the study of changes in the reflectivity of the seabed. The depth of multibeam coverage ranges from 60 to 2800 m. The data set allowed producing a Digital Elevation Models at a spatial resolution of 25 m (Fig. 1).

GEBCO (General Bathymetric Chart of the Oceans) data were used, with a resolution of 30 arc-seconds (Fig. 1) to cover unmapped areas on the shelf. These data allowed us to specify the upstream limit of canyon heads and to perform a morphometric analysis of the watersheds associated with submarine canyons.

We generated longitudinal and transverse depth profiles for each canyon using a GIS (Geographic Information System) software (Arc-Gis 10.2), thus allowing a quantified and

detailed morphometric analysis for data comparison and correlation (bathymetric profiles, cross-sections, sinuosity index, thalweg gradient, canyon and thalweg width, and valley incision depth). To map the boundaries of the submarine canyons in the study area, the manual digitizing method was used, in accordance with Heap and Harris (2008) and Huang et al. (2014).

After mapping the submarine canyons on the western Algerian margin, we applied the following filter criteria to obtain the final set of canyon polygons:

- I. The incision of the canyon head in relation to the surrounding interfluvies must be greater than 100 m;
- II. The depth range between the head and the foot of the canyon must be greater than 1000 m.

These criteria follow Harris and Whiteway (2011), and ensure that the dataset excludes out-of-canyon features such as abyssal valleys, slope gullies, and shallow plateau valleys.

The morphometric study of the canyons is based on the following parameters:

- Branching: this is a parameter similar to the “dendricity” of a canyon, the difference being that the former term is expressed in degrees and the latter’s given in number of tributaries per km². This parameter consists of defining a degree of branching that increases with each branch of the canyon.
- The longitudinal depth profile along the canyon thalweg: this profile reflects the canyon shape and represents its evolution over distance and depth. It allows for the analysis and discrimination of the type of profile (concave, convex, or linear) characterizing the canyon and to evaluate the length of the canyon.
- The gradient of the thalweg: the gradient (α) measured from the longitudinal profile of the thalweg. It reflects the inclination of the thalweg in relation to the horizontal and is expressed in degrees (°).
- The thalweg sinuosity: this is the ratio between the curvilinear length of the thalweg (L) and the distance in a straight line (D) between two points (between the head and the foot). Its value varies between 1 (in the case of a straight line) and infinity (in the case of a closed loop). A simple thalweg is considered straight when the meander index is ≤ 1.3 and meandering for values ≥ 1.3 .
- The transverse/strike depth profile of the canyon: depth profile established perpendicular to the direction of the thalweg. It shows the V or U-shaped morphology, and the presence of terraces and/or axial incisions.
- Canyon incision depth: corresponds to the distance between the lowest point of the canyon (thalweg) and the highest point of the canyon interfluves.

Other morphometric parameters were also highlighted, such as the depth at the head of the canyon, the distance of the head from the shoreline, the depth between the foot of the canyon and the surface of the canyon.

Results

The morphological study of the Algerian margin revealed the presence of more than thirty submarine canyons of different sizes and morphologies. Some of these canyons converge downslope to form a single axial canyon; others connect laterally to a main canyon or channel, while others may remain isolated. These canyons are generally NW–SE oriented, straight, and narrow, except for the Kramis canyon which is sub-parallel to the margin (slope) (Fig. 3).

The study area has been divided into three sectors: the eastern sector (between Sirat Cape and Kramis Cape), the central sector (between Kramis Cape and Aiguille Cape), and the western area (Aiguille Cape to Sigale Cape) (Fig. 3).

Canyon morphometry

Eastern sector (Cape Sirat—Cape Kramis)

This sector is characterized by a narrow or even non-existent continental shelf in front of mountainous massifs such as that of Ténès. On land, a less dense drainage system feeds the continental margin with sediments from the erosion of the continent. The peculiarity of this drainage network is the rectilinear shape of its rivers, with catchment areas in the shape of funnels, which confers a torrential regime to the drainage systems.

Three canyons in the eastern zone incise the continental shelf and are directly connected to the mouths of rivers such as Oued Damous which feeds the Damous canyon, Oued Allalah with the Allalah canyon, and Oued Tarzout in connection with the El Marsa canyon (Fig. 4). On the other hand, the Ténès and Kalah canyons incise the continental shelf but have no direct link with a river. The Colompi Islands canyon and the Guelta canyon are confined to the continental slope.

Most canyons heads are amphitheatre-shaped, with branched or dendritic forms. They generally have steep to vertical flanks with slope gradients $> 20^\circ$ and a V-shaped cross-section. The heads are hundreds of meters to several kilometers wide and their length is between 5 and 10 km. We distinguish two canyon head configurations: close to the present coastline (with a distance of 1.5 to 3 km between the canyon head and the shoreline), and isolated on the continental slope (with a distance of more than 6 km) (Fig. 4).

The canyon body presents a V or U-shaped cross-section with some intermediate shapes (Table 1). At the canyon mouth usually develop large thalwegs up to 5 km wide. The height of the canyon walls decreases to tens of meters and the mouth generally presents a U-shaped cross-section except for the Damous canyon and the canyon of the Colompi islands which present a V-shaped morphology (Fig. 6).

The longitudinal depth profiles of all canyons in the eastern sector are concave with an average slope gradient of 4.6° (Fig. 5). The canyon interfluves have a longitudinal depth profile with a concave to linear tendency in its upper part, a convex shape in the middle part, and a linear shape at its end (Fig. 5).

Some canyons exhibit the presence of knickpoints on their longitudinal profiles such as the Damous canyon, Ténès canyon, and Colompi Islands canyon (Fig. 6). These knickpoints are 100–200 m high and 300–1000 m in width. They indicate a disruption in the slope-equilibrium profile which can be explained by either tectonics deformation or lithological changes in the thalweg (Mitchell 2006).

The transverse bathymetric depth profiles across the canyons reveal a change in shape from the head to the

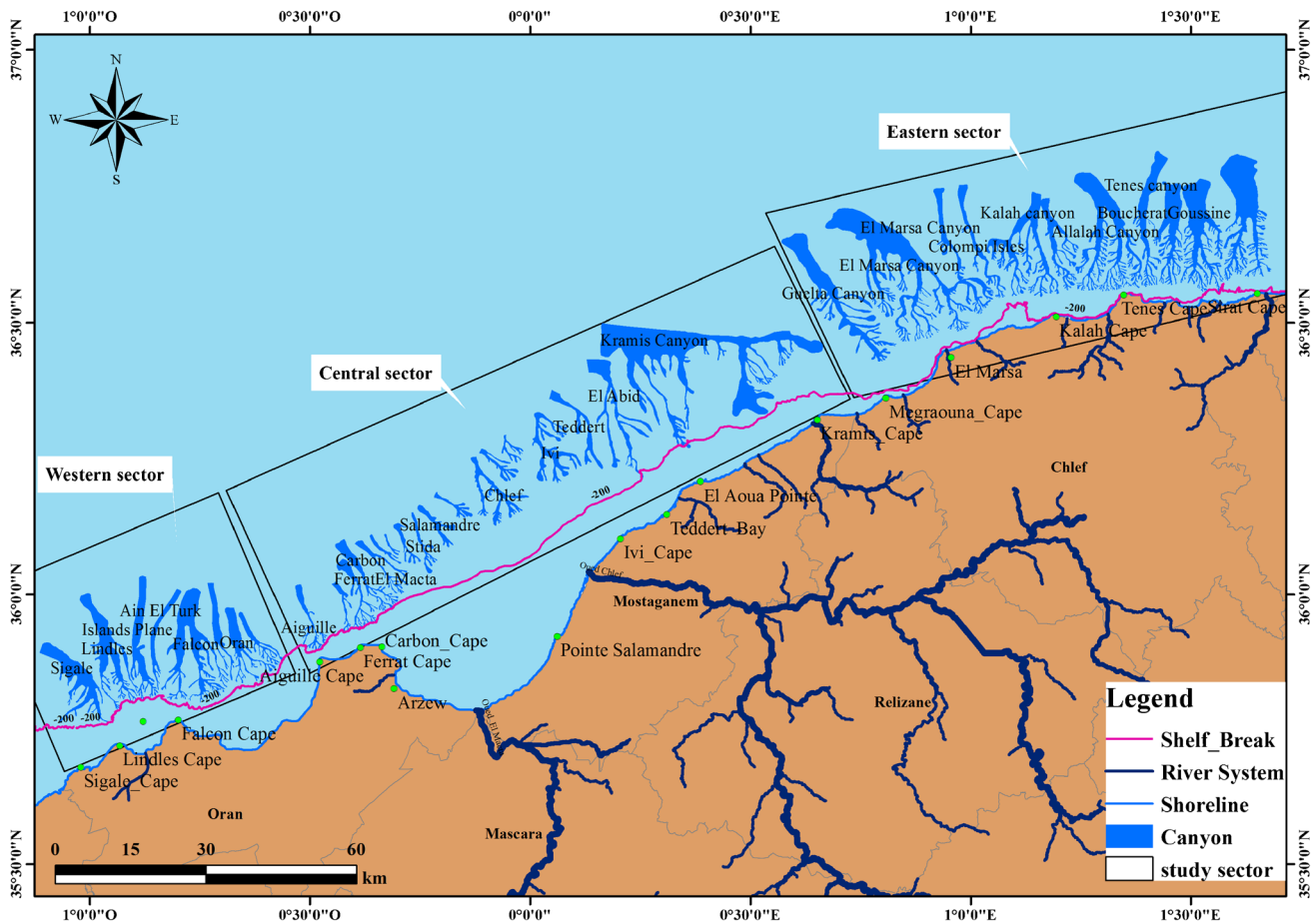


Fig. 3 Main canyons mapped along the western Algerian margin and delimitation of the three sectors

mouth, from a V-shape to a U-shape with the exception of the two canyons, Damous and Colompi Iles, which conserve the V-shape from the head to the mouth (Fig. 7a), with the existence of an axial incision at the mouth of the Damous canyon (Fig. 7a), irrefutable proof of the strength of turbidity currents that travel the axis of the canyon.

The sinuosity index of all the canyons as a whole is about 1.06 and, therefore, they can be described as straight canyons. The main orientation for all the canyons is south-north, except for the El Marsa and Guelta canyons, which have a SE-NW direction.

Canyons that incise the continental shelf and are connected a river system that has larger thalweg surfaces between 52 and 183 km² and covers more than 60 % of the Eastern sector. They also have a greater degree of branching than the other canyons (between 15 and 22), with wider and more developed mouth areas and are also less spaced between them on average between 2 and 3 km apart and can reach incision depths of more than 400 m (Table 1).

Central sector (Cape Kramis—Cape Aiguille)

This sector is characterized by a relatively wide continental shelf that varies between 10 and 30 km, especially opposite the large bay of Arzew (Fig. 2). The largest watershed in the central zone is the Chlef watershed. It is 300 km long, has a gentle slope, 1° to 2° on average gradient and drains a 26,750 km² basin with an elongated shape. Valley Chlef is characterized by a sinuous shape that favors the accumulation of sediments in the hinterland. Valley Chlef originates from the Tellian Atlas and diversifies in front of the large bay of Arzew. It is the main source zone in sediment of the central region.

The majority of canyons in the central sector incise the continental slope to a depth of 200 m, but they do not reach the continental shelf. Therefore, they can be described as slope-confined canyons or “headless canyon.” These canyons are parallel to the slope and are generally small with an average length of 18 km and a very high thalweg gradient (8°), with the exception of the Kramis canyon which

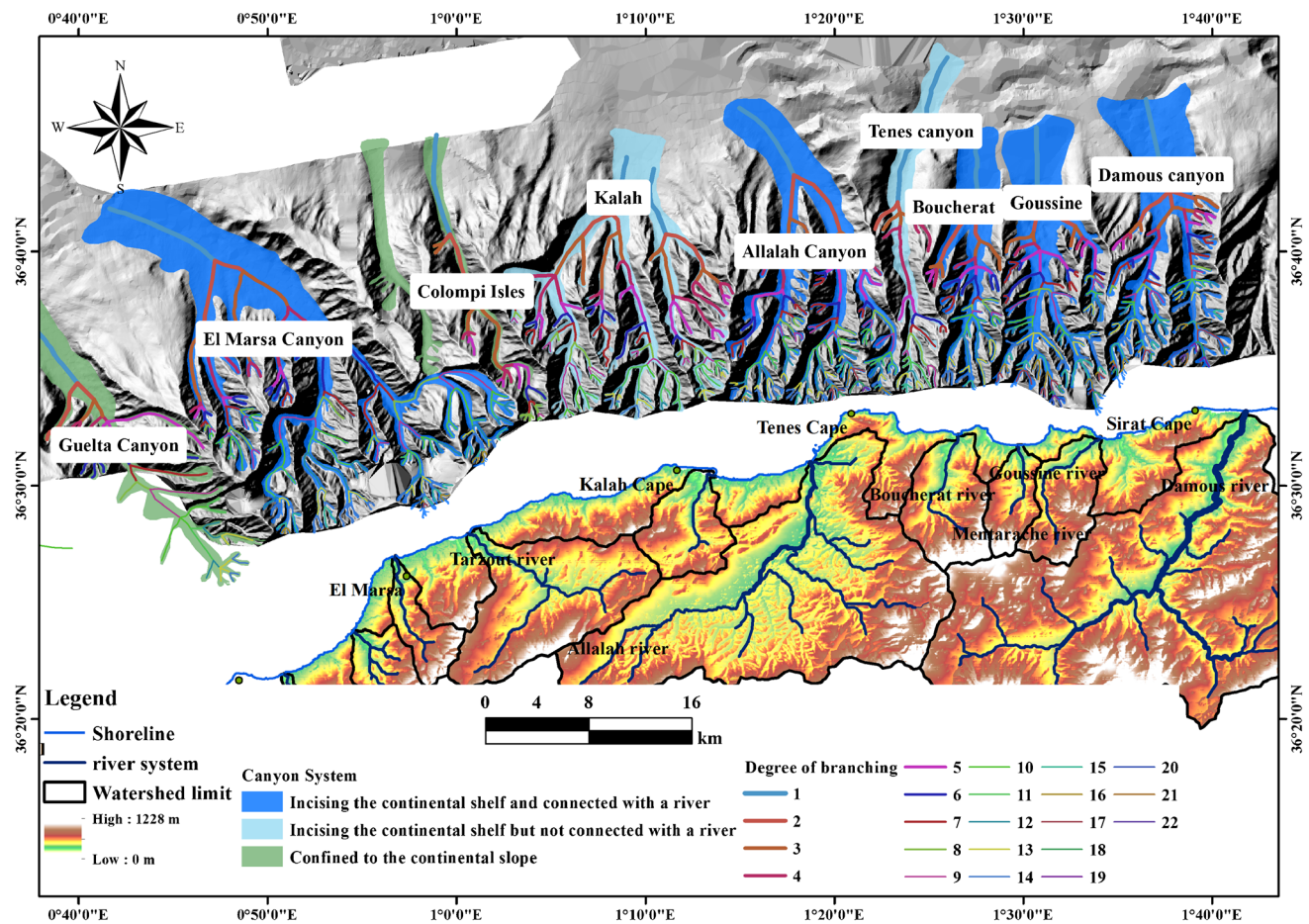


Fig. 4 Physiographic map illustrating the degree of branching of the canyons with the associated drainage system on land in the eastern sector

presents a very particular morphological signature on the continental slope and a sub-perpendicular direction to the slope and which extends over a length of 40 km with a more or less important gradient of the thalweg (2.8°).

The canyon heads in the sector have a simpler morphology compared to other sectors, except for Ivi Canyon that shows an amphitheatre shape. These canyon heads have a lower degree of branching than in the eastern sector (The maximum branching is 13) (Fig. 8), with steep to vertical flanks. The canyon heads are hundreds of meters to a few kilometers wide and its length is between 3 and 5 km. The canyon body may present a V or U-shaped cross-section with some intermediate profiles (Table 1). The width of the canyon valley is almost constant from head to mouth (400–500 m wide). On the other hand, the canyon mouth zone is less developed with narrowing of the thalweg towards the downstream, but also an increase in the average gradient (up to 15°) (Fig. 8) and with V-shaped cross-sections, except for the case of Kramis Canyon, which is characterized by a well-developed and wider mouth zone (Fig. 8).

The longitudinal depth profiles of most canyons in the central sector are convex to linear with an average gradient of 7.6° (Fig. 9). The interfluvial longitudinal depth profiles have a clear convex shape (Fig. 9). The average slope is 6° and the maximum of 13° . On the other hand, the Kramis, Carbon, Ferrat, and Aiguille canyons have rather a concave longitudinal depth profile with an average slope of 2.8° to 8° , and which decreases locally from the head to the mouth.

Canyons with a convex to linear longitudinal depth profile are characterized by the presence of knickpoints, which generate steep step-like features on the longitudinal profile (Fig. 9). These knickpoints are about 100 to 300 m high and over 500 and 2000 m distance are interpreted as escarpments at the foot of the slope.

Similar to the canyons in the eastern zone, the transverse bathymetric profiles of the canyons in the central region show a change in shape from head to mouth, from V-shaped to U-shaped, with the exception of Stida Canyon, which conserves the V-shape from head to mouth (Fig. 7b).

The average sinuosity index of the canyons is about 1.05, which characterizes a rectilinear shape. The main orientation

Table 1 Descriptions of canyon morphometric characteristics

Canyon name	Canyon valley area (km ²)	Mean slope of thalweg (°)	Distance from shoreline (km)	Depth in canyon head (m)	Depth in canyon mouth (m)	Sinuosity	Degree of branching	Depth of incision at the canyon head (m)	Depth of incision at the canyon body (m)	Depth of incision at the canyon mouth (m)	Canyon length (km)	Transverse depth profile at the canyon head	Transverse depth profile at the canyon body	Transverse depth profile at the canyon mouth	Canyon Type
Eastern sector															
Damous canyon	106.50	5.55°	3	-180	-2640	1.08	22	200	400	250	25	V	U and V	V	1
Goussine canyon	80.98	5.94°	1.45	-90	-2620	1.033	20	180	400	180	24	V	U	U	1
Boucherat canyon	51.44	5.45°	3	-420	-2620	1.028	15	210	300	130	21	V	U and V	U	1
Tènes canyon	44.58	4.42°	1.9	-480	-2650	1.007	15	90	380	150	22	V	U	U	2
Allalah Canyon	98.34	4.51°	1.2	-410	-2680	1.1	19	100	500	90	25.6	V	U	U	1
Kalah canyon	109.82	4.54°	3.5	-480	-2610	1.09	15	130	400	90	23.5	V	U	U	2
Colompi-Isles Canyon	23.80	4.25°	6	-430	-2540	1.11	15	200	350	100	26	V	V and U	V	3
Central sector															
Kramis Canyon	254.80	2.7°	6.5	-780	-2600	1.01	13	170	220	160	38.7	U	U	U	3
El Abid Canyon	45.42	5.9°	8.6	-140	-2620	1.04	7	120	400	350	23	V	V	U	2
Teddert Canyon	20.76	5.8°	9.6	-390	-2620	1.06	6	180	260	95	22	V	V	V	3
Ivi Canyon	37.17	7.3°	17	-800	-2620	1.08	9	40	300	70	17	V	U	U	3
Chlef Canyon	26.92	6.54°	18	-540	-2620	1.11	9	140	450	200	17.2	U	V	U	3
Sala-mandre Canyon	13.58	9.08°	25	-700	-2620	1.012	5	300	480	120	11.3	U	U	V	3

Table 1 (continued)

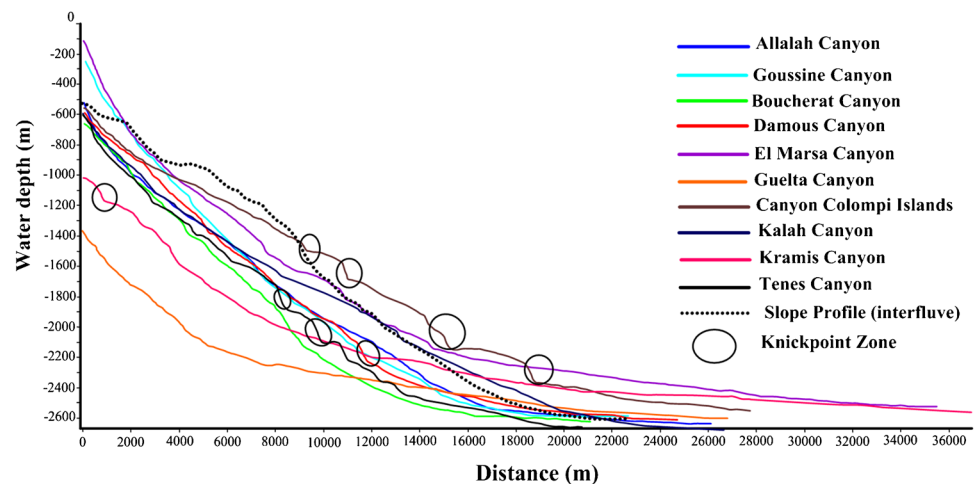
Canyon name	Canyon valley area (km ²)	Mean slope of thalweg (°)	Distance from shoreline (km)	Depth in canyon head (m)	Depth in canyon mouth (m)	Sinuosity	Degree of branching	Depth of incision at the canyon head (m)	Depth of incision at the canyon body (m)	Depth of incision at the canyon mouth (m)	Canyon length (km)	Transverse depth profile at the canyon head	Transverse depth profile at the canyon body	Transverse depth profile at the canyon mouth	Canyon Type
Stida Canyon	7.67	10.2°	28	-440	-2620	1.02	5	100	500	120	12	V	V	V	3
El Macta Canyon	13.81	10.8°	30	-320	-2560	1.03	9	80	220	80	15	V	V and U	V	3
Carbon Canyon	14.55	8.2°	6.8	-140	-2600	1.04	10	80	200	140	18	V	V and U	V	2
Ferrat Canyon	14.55	8.9°	3.9	-180	-2600	1.09	9	130	300	110	17	V	U	U	2
Aiguille Canyon	9.02	9.5°	1.56	-120	-2320	1.06	11	80	160	70	16	V	U	U	2
Western sector															
Oran Canyon	25.32	7.3°	9.7	-120	-2480	1.1	10	120	200	70	19	V	U	U	2
Falcon Canyon	82.47	5.2°	4	-320	-2560	1.11	15	150	260	100	26	V	U	U	3
Ain El Turk Canyon	17.59	6.1°	7	-580	-2560	1.05	4	70	130	55	27	V	V	U	3
Islands Plane Canyon	41.41	5.4°	6	-180	-2560	1.03	10	140	200	70	27.5	V	V	V	2
Lindles Canyon	58.60	5.8°	7	-160	-2440	1.04	15	120	280	70	25	V	U	U	2
Sigale Canyon	54.61	4.6°	4.87	-680	-2380	1.05	10	160	320	140	24	V	U	U	3

1: Canyons incising the continental shelf and connected with a river.

2: Canyons incising the continental shelf but not connected with a river.

3: Canyons confined to the continental slope.

Fig. 5 Canyons longitudinal depth profiles in the Eastern sector



for all the canyons is NW–SE, except for the Kramis Canyon which has an E–W orientation (Fig. 8).

Moving westward from the Bay of Arzew, the canyons incise the continental shelf down to 120 m water depth, but without any connection to a hydrographic network. The majority of canyons in the central sector are characterized by very small valley areas between 9 and 45 km², except for the Kramis Canyon that has a valley area of 255 km² (Table 1). These canyons also are more widely spaced, averaging between 5 and 7 km, with incision depths as deep as 300 m (Table 1).

Western sector (Cape Aiguille—Cape Sigale)

The western sector is characterized by a narrow continental shelf that varies from 2 km off the capes to 10 km wide off the Bay of Oran. The drainage system is rather non-existent (Fig. 10); the surface of coastal watersheds varies between 40 and 76 km², with elongated basin shapes.

In the western sector, there are canyons that incise the continental shelf up to a depth of 120 m (e.g. Oran Canyon), but they are not connected to a river system, and there are also canyons confined to the continental slope (Fig. 10).

All the canyons in this sector have an S–N direction. The average length of the canyons is 24 km, with an average thalweg gradient of 6°.

The canyon heads have a simple morphology, with a higher degree of branching than the central sector (up to 15). The canyon head walls are very steep to sub-vertical with an average slope of 32° and V-shaped cross-sections. The canyon body is U-shaped (Table 1), except for the Ain El Turk canyon, which is V-shaped (Fig. 7c). The canyon mouth is more or less developed (Fig. 10), except for the falcon and Sigale canyon, which presents a very wide mouth zone between 3 and 5 km.

The longitudinal depth profiles of all canyons in the zone have a slightly steeper concave shape than those of

canyons in the eastern zone (Fig. 11), identical to the profile of the interfluves with an average slope gradient of 6° that decreases locally from the head to the mouth (Fig. 11). The peculiarity of the longitudinal depth profiles of the western zone is the absence of *knickpoints* on the topographic profile (Fig. 11).

The average sinuosity index of the canyons average is about 1.06, which coincides with an almost rectilinear shape.

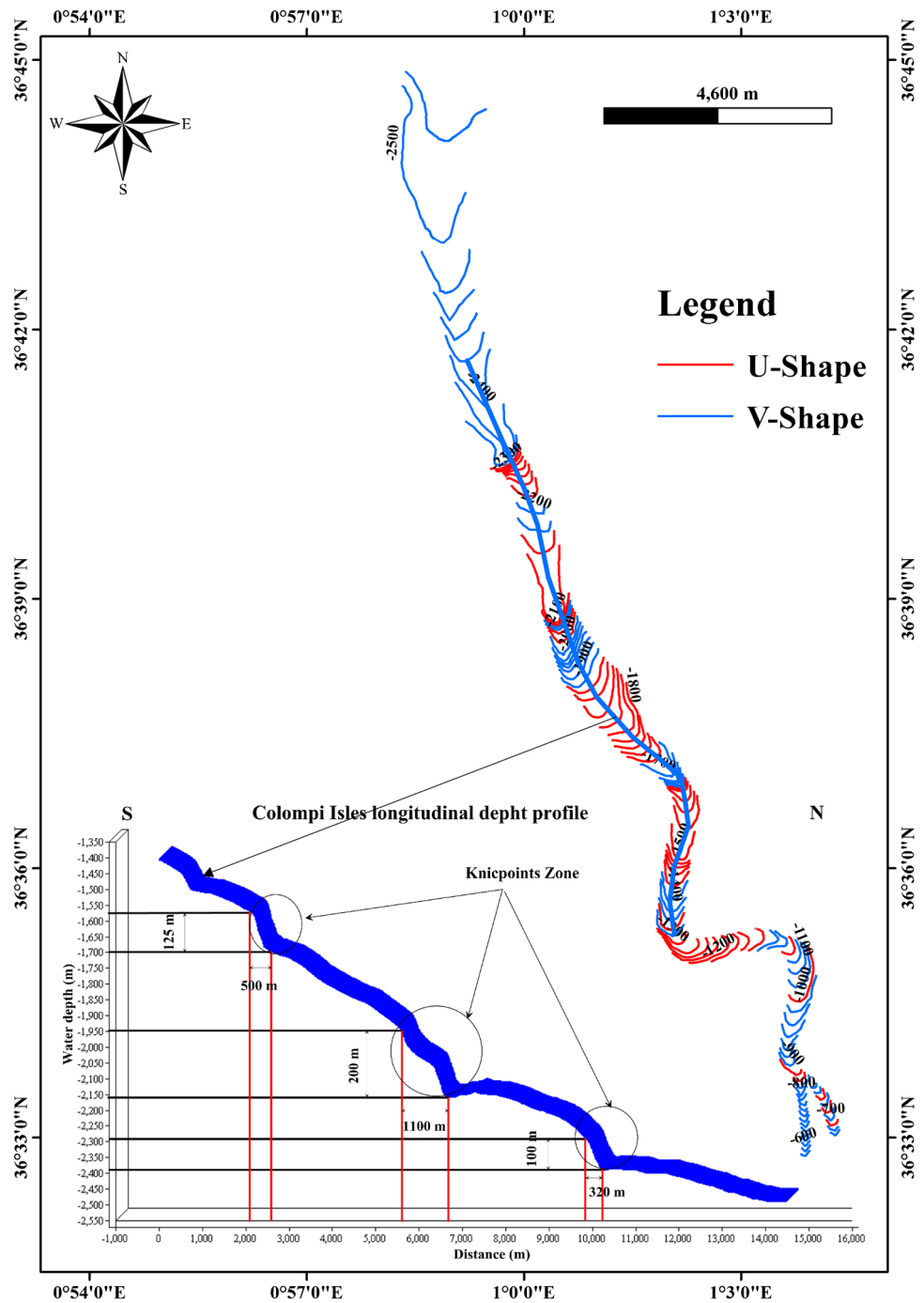
Canyon activity

A canyon is considered active when sediment-laden and erosive gravity currents take its course and settle at the foot of a continental slope. It is inactive when, cut off from direct sedimentary inputs, it slowly fills in through hemiplegic sedimentation. The activity of a canyon therefore depends strongly on the location of the head of the canyon on the continental margin, on its connection with a sub-aerial river system and on the variation of the source's inputs over time.

The recent activity of the canyons, of the West Algerian margin, can be deduced thanks to the interpretation of the reflectivity map, based on the variation of grey levels. Thus, the higher the grey level (dark grey), the greater the activity, and the floor surface corresponds to an area where the sediments are restructured and disturbed (with coarse deposits), and conversely when the shades tend towards white (light grey), this indicates little or no activity; the surface sediments are in calm environments (fine hemiplegic deposits).

From the backscattering data (Fig. 12), it can be seen that the bottom of the canyons in the East and West zones are darker than the bottom of the canyons in the central zone. This high back-scattering might reflect recent (Holocene) turbiditic activity as observed on sediment cores from this area by Ratzov et al. (2015). Turbiditic activity is also at the origin of the formation of the deep sea fan at the mouth of the Kramis canyons initiated after the Messinian Salinity Crisis (Babonneau et al. 2012).

Fig. 6 Canyon Colompi Isles longitudinal and cross-section depth profiles



Discussion

The morphometric analysis of the submarine canyons on the western Algerian margin shows changes in their geometric configuration, from east to west and from the top to the bottom of the continental slope.

By observing the longitudinal depth profiles of the canyons of the western Algerian margin, we first note that the average thalweg gradient is very high ($\sim 5^\circ$) for all the canyons, with the exception of Kramis canyon ($< 5^\circ$) (Fig. 9).

From east to west, we can distinguish two categories of longitudinal profiles characterizing the evolution of the canyons. In the eastern part of the margin, the canyon thalwegs present concave longitudinal depth profiles, whereas the canyon interflues are characterized by a linear to convex longitudinal profile (Fig. 5), which suggests that the canyons have already reached a state of equilibrium (Gaudin et al. 2006). Although the deep V-shaped cross-sectional profiles in the head of the canyons suggest that erosion is still very active, mainly due to the high slope angle and the direct

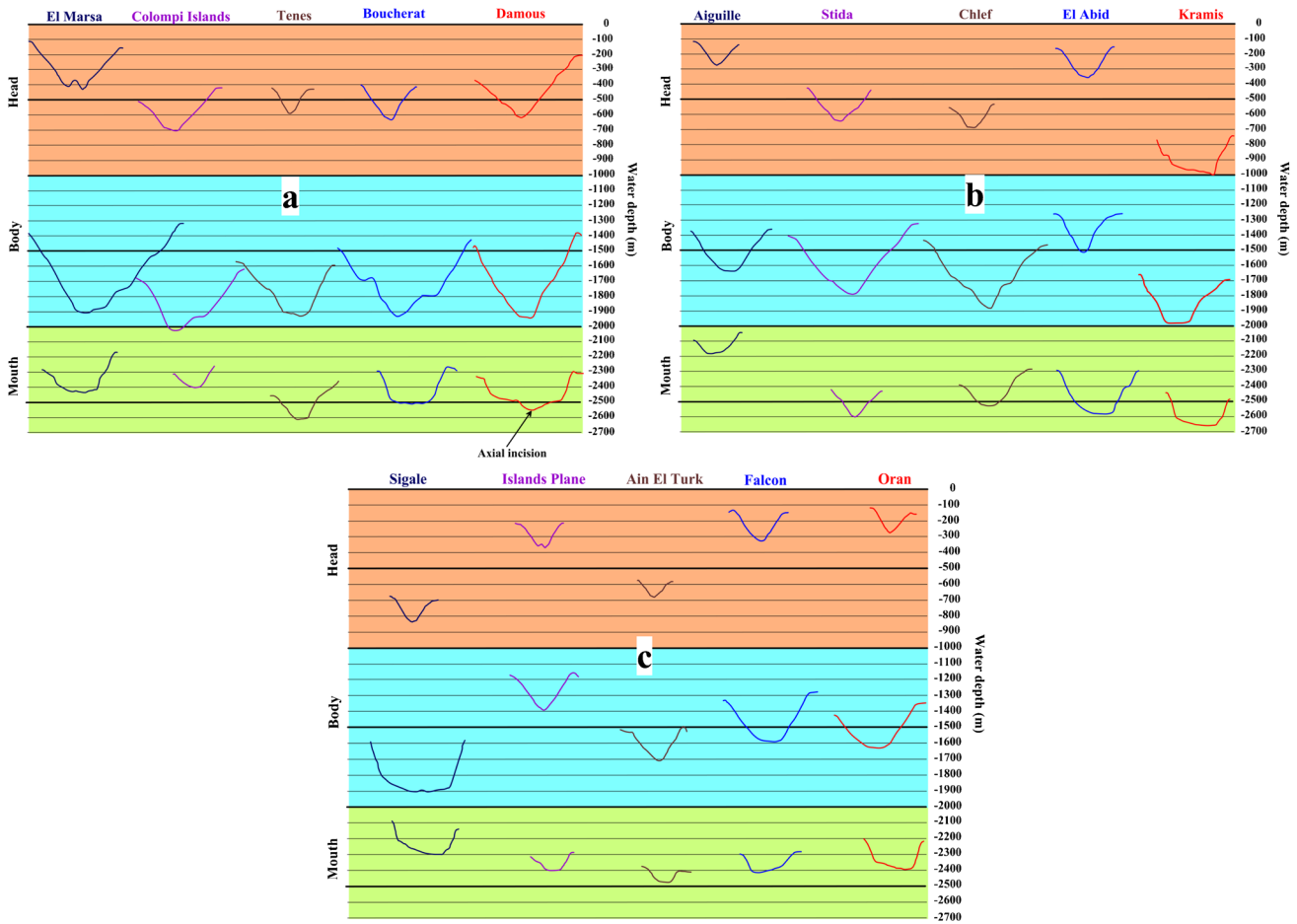


Fig. 7 Transverse bathymetric profiles along canyons showing U- or V-shaped profiles and canyon depths

connection to a drainage system, the U-shaped cross-section in the body and mouth parts suggests that the canyons have reached their maximum incision depth and are now evolving by lateral erosion through destabilization of the flanks.

In the eastern part of the margin, the thalwegs show knickpoints in their longitudinal profiles (disturbance of the equilibrium profile), which can be explained either by tectonic deformation or lithological changes in the thalweg (Mitchell 2006). The striking feature of these knickpoints is their location between the mid-slope and the foot of the slope (between a depth of -1600 m and -2400 m), together with their large dimensions in height and length (Figs. 6–7–10), which suggests the possibility of a tectonic feature persisting on this depth range, probably related to uplift mechanisms under a compressive regional tectonic setting. The canyons in the Eastern sector can therefore be interpreted as mature canyons developing on a margin controlled by compressive tectonics, with steep slopes and a narrow continental shelf favoring erosive processes.

In the central part of the margin, the thalweg and interflaves of the canyons present convex-up longitudinal depth

profiles (Fig. 9). The canyons have not yet reached an equilibrium profile and eroding processes are, therefore, expected to be strongly active. In fact, the V-shaped cross-sections are highly developed in the canyon head and body parts of the thalweg axis. On the other hand, the mouth displays a U-shaped cross-section (Fig. 7b). Only the Kramis canyon is characterized by a concave longitudinal depth profiles (Fig. 9) and a U-shaped cross-section from the head to the mouth (Fig. 7b), thus can be interpreted as a mature canyon. On the other hand, the Carbon, Ferrat, and Aiguille canyons are similar to the Kramis canyon, with a concave longitudinal profile but a V-shaped cross-section. In other words, the El Abid, Teddert, Ivi, Chlef, Salamander, and Stida canyons can be interpreted as immature or juvenile canyons. The present convex longitudinal profiles of the thalwegs and their interflaves should be strongly constrained by the deformation and uplift of the margin. Along the convex profiles, the angles of inclination of the canyon head and body are of the order of $8-10^\circ$ and $4-5^\circ$, respectively, while the mouth area is too steep $6-7^\circ$. This may suggests that the upper edge where the head and body have been lifted relatively less

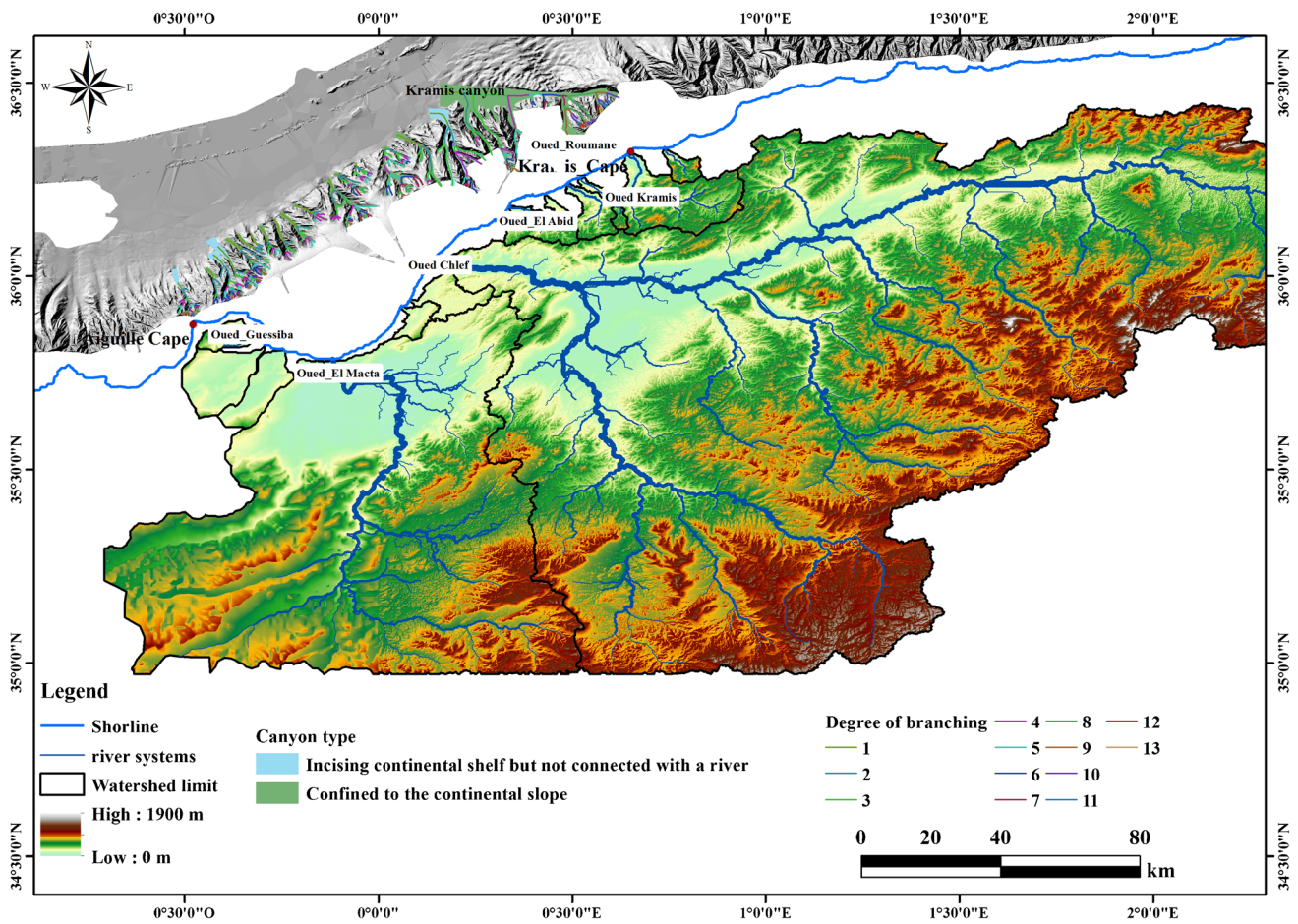


Fig. 8 Physiographic map illustrating the degree of canyon branching with the associated drainage system on land in the central sector

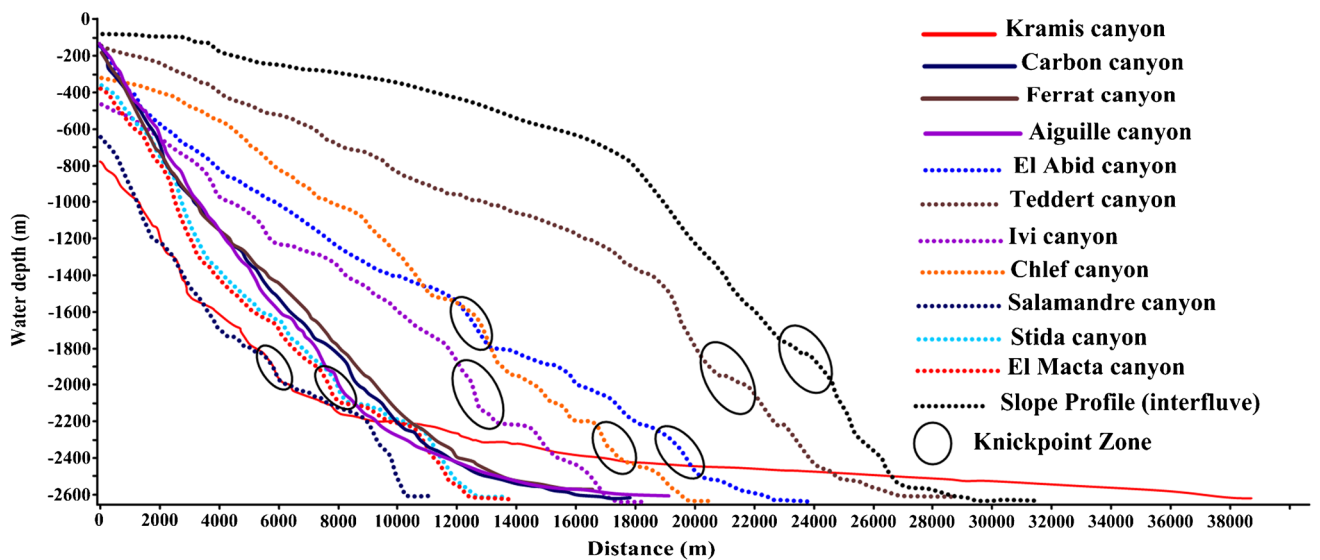
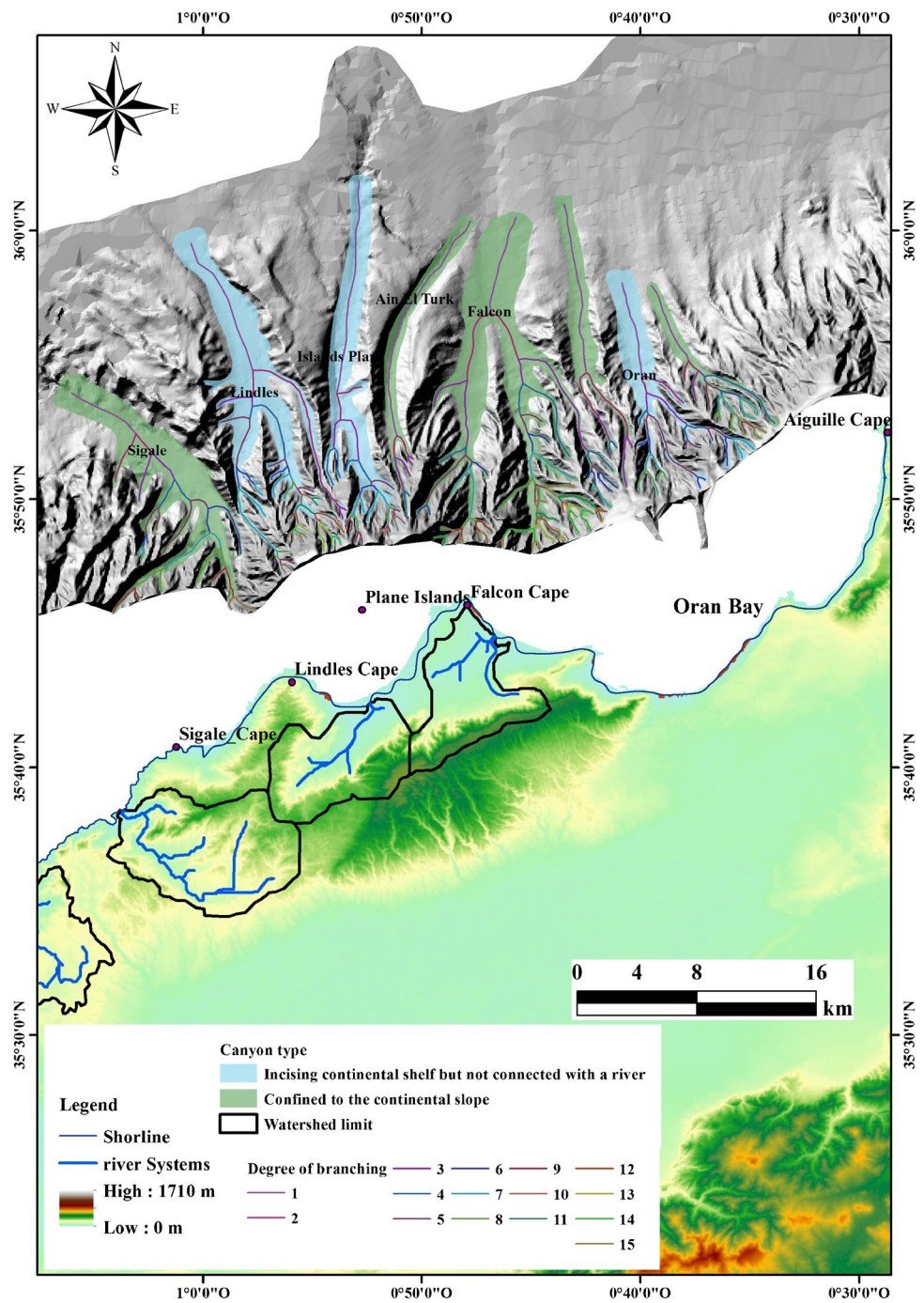


Fig. 9 Longitudinal depth profiles of canyons in the central region. The thick lines: concave profile and slope profile; the dashed thin line: convex profile

Fig. 10 Physiographic map illustrating the degree of branching of canyons with associated watersheds ashore in the western sector



than the lower edge where the mouth area has been tilted northwards with a large increase in the slope angle.

In the western part of the margin, the thalweg and interfluvies of the canyons present slightly steeper concave longitudinal depth profiles (Fig. 11), suggesting that they have already reached a state of equilibrium (Gaudin et al. 2006), with deep V-shaped transverse depth profiles in the canyon heads (Fig. 7c), suggesting that erosion is still very active. This is mainly due to the steep slope angle as there is no direct connection to a drainage system (Fig. 10). As there

are no knickpoint zones on the longitudinal profiles of the canyons as a whole, it can be said that the western zone is little or not affected by tectonics.

The variations in convex versus concave thalweg profiles might be due to differential compression along the margin.

From the data of the reflectivity map (Fig. 12), we can estimate that the canyons of the eastern sector are more active, as they are characterized by the darkest tones in terms of imagery; which suggests the presence of a coarse-grained facies on the canyon bottoms. In the case of the

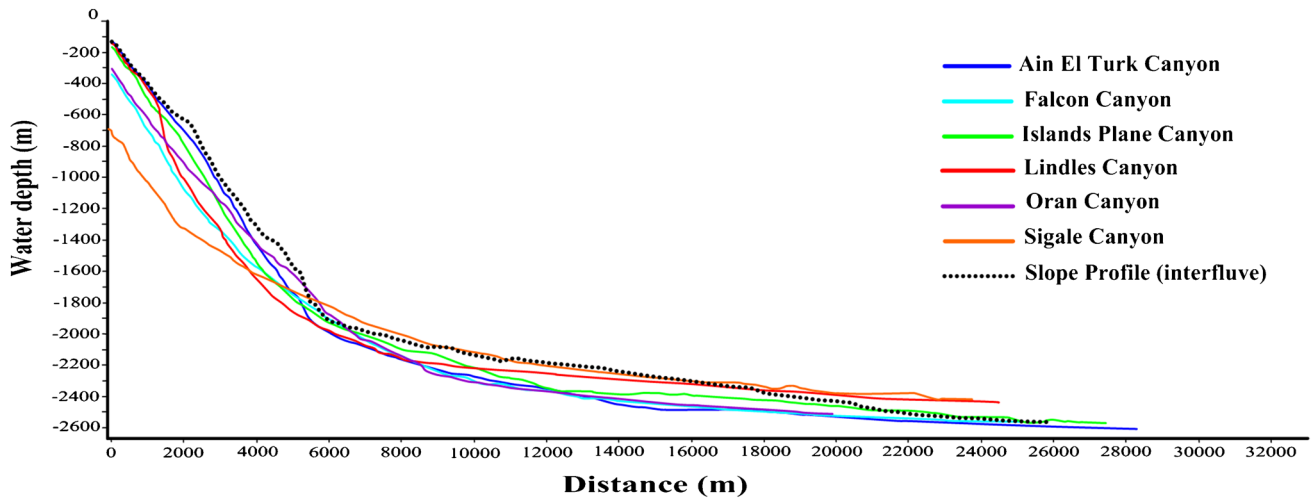


Fig. 11 Longitudinal profiles of canyons in the western sector

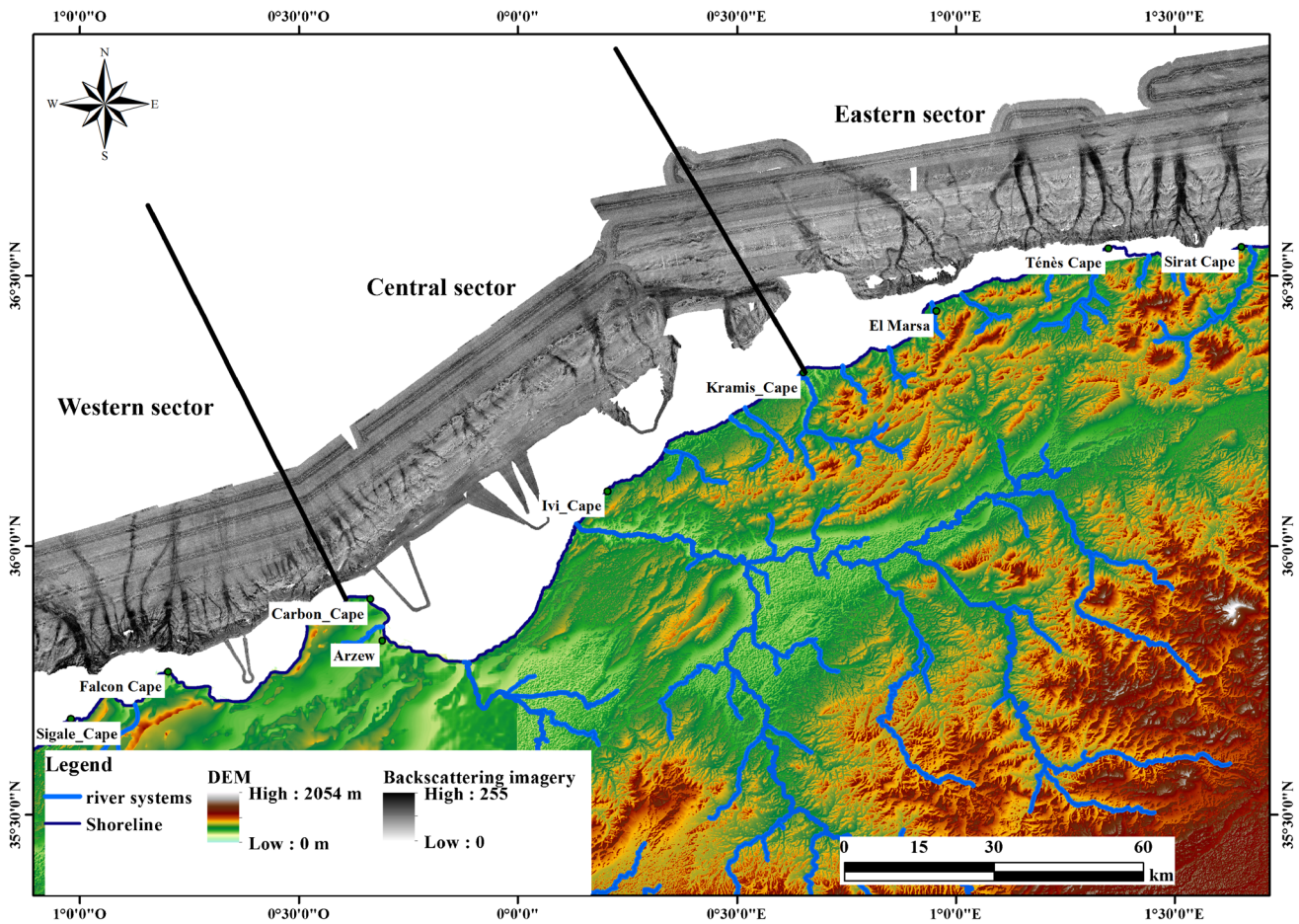


Fig. 12 Backscattering map of the study area. The reflective (dark) character indicates a rough background and relatively recent canyon activity

canyons in the central sector, the majority of canyons show very low backscattering with the exception of the Kramis Canyon is marked by dark tones (high reflectivity); this suggests the deposition of coarse-grained material in the canyon bottom, due to the narrowness of the continental shelf, 6.5 km between the mouth of the Kramis Valley and the head of the thalweg.

The canyons in the western sector are marked by dark tones (high reflectivity); this usually indicates the presence of a coarse-grained facies on the canyon bottoms, and this activity extends to the abyssal plain, which potentially testifies the action of erosive flows, most probably related to turbidity currents.

The current morphology of the margin has influenced the distribution of canyons. In sector with a narrow continental shelf, the canyons are longer, deeper, and well developed and incise the continental shelf and with a higher degree of branching and a greater depth of incision (Table 1); on the other hand, in sector where the continental shelf is wide, the canyons are confined to the slope and less developed, with a shorter length and less branching and a shallower depth of incision and they are steeper.

The geodynamic history of the margin has influenced the morphology of the slope, since STEP (Subduction Transform Edge Propagator) type margins are distinguished from other margins by a narrow and steep continental slope (3° to 9°) (Le Pichon and Fox 1971; Scrutton 1976). In the three sectors studied on the margin, canyon cross-sections change downslope from V-shaped to U-shaped (Fig. 7). Such longitudinal depth evolution has already been observed in the marine area of western Iberia (Arzola et al. 2008). Comparison between the three zones revealed that V-shaped cross-sections are associated with a slope gradient greater than 5° , whereas U-shaped cross-sections appear where the slope angle is less than 5° . The formation of V or U-shaped cross-sections could therefore be strongly constrained by a critical slope angle of the continental slope of about 5° . This critical angle is thought to have a direct effect on the erosive capacity of gravity flows, with a slope angle greater than 5° giving the flows sufficiently high kinetic energy to significantly increase their erosive power (Brothers et al. 2013).

It has already been shown that tectonics influence the location of canyons (Antobreh and Krastel 2006; Mountjoy et al. 2009). On the Algerian margin, the Kramis Canyon differs from the other canyons of the margin by its East–West orientation. It is believed that the canyon was carved in a collapse zone linked to the presence of a strike slip fault, which is located between two geological domains of different age and nature (the internal and the external domains) (Domzig et al. 2006). In addition, the knickpoints, which interestingly are all at the same depth range, may be the expression of compressive tectonics.

Conclusion

Based on high-resolution multibeam bathymetry and imagery data, obtained from EM 300, we can see that the western Algerian margin is characterized by morphologic contrast, from east to west and from the top to the bottom of the continental slope. Different factors control the variation of morphology of the canyons, their initiation and evolution on the margin, notably the width of the continental shelf, sediment supply, margin morphology, and compressive tectonics.

In conclusion, we can say that sector where the continental shelf is narrow or even non-existent canyons are very incised, highly dendritic and ramified, highly developed, and apparently very active; their origin may be associated with a drainage system. These canyons have concave longitudinal depth profiles and are designated as mature because they reach an equilibrium longitudinal profile and characterize the morphology of a young margin. In sector where the continental shelf is wide, the slope in front of the Bay of Arzew is singularly devoid of large active canyons, whereas on land, we are in front of one of the largest rivers in Algeria, due to its drainage network and its length (Chlef River). The presence of the continental shelf probably plays a role in trapping sediments coming from the continent, and the attenuation of the energy coming from the rivers, the canyons confined to the slope and disconnected from a sub-aerial river system are initially formed by mass movements at the slope (for several different reasons: change in lithology and/or accumulation rate and/or fluid escape along preferential conduits, destabilization associated with tectonic uplift) and evolve up the slope in a second stage by retrogressive erosion. These canyons present a convex longitudinal depth profiles, and are called immature or juvenile canyons because they have not yet reached a longitudinal profile of equilibrium and characterize the morphology of a passive margin reactivated in compression. The West Algerian margin is therefore considered to be a young margin reactivated in compression.

Canyons appear to be good markers of margin deformation that can be reflected by the deformation of the longitudinal depth profile of the canyon (convex trend). We could thus, based on the morpho-structural evolution of the canyons, corroborate the hypothesis of a deformation of the western Algerian margin increasing towards the east.

High-resolution seismic profiles along the canyon axis are recommended to constrain the internal architecture of the canyons in order to propose a model of canyons evolution in the study margin.

Acknowledgements We wish to thank IFREMER and the crew of the R/V Le Suroît, led by Captain A. Werly for their support during the

Maradja cruise. We are indebted to SHFN ('Service hydrographique des forces navales', Algeria) for allowing this study.

Declarations

Competing interests The authors declare no competing interests.

References

- Allen S, Madron XDD (2009) A review of the role of submarine canyons in deep-ocean exchange with the shelf. *Ocean Sci* 5:607
- Antobreh AA, Krastel S (2006) Morphology, seismic characteristics and development of Cap Timiris Canyon, offshore Mauritania: a newly discovered canyon preserved-off a major arid climatic region. *Marine Petrol Geol* 23:37–59
- Arzola RG, Wynn RB, Lastras G, Masson DG, Weaver PP (2008) Sedimentary features and processes in the Nazaré and Setúbal submarine canyons, west Iberian margin. *Marine Geology* 250:64–88
- Auzende JM (1978) Histoire tertiaire de la Méditerranée occidentale. Université de Paris VII, Paris
- Babonneau N, Savoye B, Cremer M, Klein B (2002) Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. *Mar Pet Geol* 19:445–467
- Babonneau N, Cattaneo A, Savoye B, Barjavel G, Déverchère J, Yelles K (2012) The Kramis fan offshore western Algeria: the role of sediment waves in turbiditic levee growth SEPM Special. Publication 99:293–308
- Badji R et al (2014) Strike-Slip Deformation at the Ocean-Continent Boundary of the Algerian Continental Margin: Surface Expression of a STEP? AGUFM 2014:T51B-4609
- Baztan J et al (2005) Axial incision: The key to understand submarine canyon evolution (in the western Gulf of Lion). *Marine Petrol Geol* 22:805–826
- Berné S et al. (2002) Carte morpho-bathymétrique du Golfe du Lion, notice explicative Ifremer. Brest 48
- Bertoni C, Cartwright J (2005) 3D seismic analysis of slope-confined canyons from the Plio-Pleistocene of the Ebro Continental Margin (Western Mediterranean). *Basin Res* 17:43–62
- Bouillin JP (1986) Le " bassin maghrebin"; une ancienne limite entre l'Europe et l'Afrique a l'ouest des Alpes. *Bull Soc Géol France* 2(4):547–558
- Bracene R (2002) Géodynamique du nord de l'Algérie. Cergy-Pontoise
- Brothers DS, Uri S, Andrews BD, Chaytor JD, Twichell DC (2013) Geomorphic process fingerprints in submarine canyons. *Mar Geol* 337:53–66
- Clauzon G (1982) Le canyon messinien du Rhone; une preuve decive du " desiccated deep-basin model"(Hsue, Cita and Ryan, 1973). *Bull Soc Géol France* 7:597–610
- Covault JA, Romans BW, Graham SA, Fildani A, Hilley GE (2011) Terrestrial source to deep-sea sink sediment budgets at high and low sea levels: Insights from tectonically active Southern. *Calif Geol* 39:619–622
- Cronin BT, Akhmetzhanov AM, Mazzini A, Akhmanov G, Ivanov M, Kenyon NH (2005) Morphology, evolution and fill: implications for sand and mud distribution in filling deep-water canyons and slope channel complexes. *Sediment Geol* 179:71–97
- Daly RA (1936) Origin of submarine canyons. *Am J Sci* 31:401–420
- Domzig A et al (2006) Searching for the Africa-Eurasia Miocene boundary offshore western Algeria (MARADJA'03 cruise). *Comptes Rendus Geosci* 338:80–91
- El-Robrini M (1986) Evolution morphostructurale de la marge algérienne occidentale (Méditerranée occidentale): Influence de la néotectonique et de la sédimentation. Paris 4
- Farre JA, McGregor BA, Ryan WB, Robb JM (1983) Breaching the shelfbreak: passage from youthful to mature phase in submarine canyon evolution
- Frizon de Lamotte D, Saint Bezar B, Bracène R, Mercier E (2000) The two main steps of the Atlas building and geodynamics of the western Mediterranean. *Tectonics* 19:740–761
- Gargani J, Rigollet C (2007) Mediterranean Sea level variations during the Messinian salinity crisis. *Geophys Res Lett* 34(10):29885
- Gaudin M et al (2006) Massive sand beds attributed to deposition by dense water cascades in the Bourcart canyon head, Gulf of Lions (northwestern Mediterranean Sea). *Marine Geol* 234:111–128
- Goff JA (2001) Quantitative classification of canyon systems on continental slopes and a possible relationship to slope curvature. *Geophys Res Lett* 28:4359–4362
- Govers R, Wortel MJR (2005) Lithosphere tearing at STEP faults: Response to edges of subduction zones. *Earth Planet Sci Lett* 236(1):505–523
- Green A (2011) Submarine canyons associated with alternating sediment starvation and shelf-edge wedge development: Northern KwaZulu-Natal continental margin, South Africa. *Marine Geology* 284:114–126
- Green AN, Goff JA, Uken R (2007) Geomorphological evidence for upslope canyon-forming processes on the northern KwaZulu-Natal shelf, SW Indian Ocean, South Africa. *Geo-Marine Lett* 27:399–409
- Greene H, Maher N, Paull C (2002) Physiography of the Monterey Bay National Marine Sanctuary and implications about continental margin development. *Mar Geol* 181:55–82
- Harris PT, Whiteway T (2011) Global distribution of large submarine canyons: geomorphic differences between active and passive continental margins. *Mar Geol* 285:69–86
- Heap A, Harris P (2008) Geomorphology of the Australian margin and adjacent seafloor. *Aust J Earth Sci* 55:555–585
- Heezen BC, Ewing WM (1952) Turbidity currents and submarine slumps, and the 1929 Grand Banks [Newfoundland] earthquake. *Am J Sci* 250(12):849–873
- Heezen BC, Ericson DB, Ewing M (1954) Further evidence for a turbidity current following the 1929 Grand Banks earthquake. *Deep-Sea Res* 1(4):193–202
- Hill V, Cota G (2005) Spatial patterns of primary production on the shelf, slope and basin of the Western Arctic in. *Deep Sea Res Part II* 52:3344–3354
- Hsü K, KJ H, MB C, WBF R (1973) The origin of the Mediterranean evaporites
- Huang Z, Nichol SL, Harris PT, Caley MJ (2014) Classification of submarine canyons of the Australian continental margin. *Mar Geol* 357:362–383
- Jobe ZR, Lowe DR, Uchytel SJ (2011) Two fundamentally different types of submarine canyons along the continental margin of Equatorial Guinea. *Mar Pet Geol* 28:843–860
- Krastel S, Schmincke H-U, Jacobs C (2001) Formation of submarine canyons on the flanks of the Canary Islands. *Geo-Mar Lett* 20:160–167
- Le Pichon X, Fox PJ (1971) Marginal offsets, fracture zones, and the early opening of the North Atlantic. *J Geophys Res* 76:6294–6308
- Leclaire L (1972) La sédimentation holocène sur le versant méridional du bassin algéroléaire (précontinent algérien) These d'Etat, Paris
- Matougui R (2008) Etude des mouvements gravitaires sur la marge algérienne, exemple de la marge continentale du Dahra occidental. Dissertation, University of USTHB Algeria
- McHugh CM, Damuth JE, Mountain GS (2002) Cenozoic mass-transport facies and their correlation with relative sea-level change, New Jersey continental margin. *Marine Geol* 184:295–334

- Medaouri M, Bracene R, Déverchère J, Graindorge D, Ouabadi A, Yelles-Chaouche A (2012) Structural styles and neogene petroleum system around the Yusuf-Habibas ridge (Alboran basin, Mediterranean sea). *Lead Edge* 31:776–785
- Medaouri M et al (2014) The transition from Alboran to Algerian basins (Western Mediterranean Sea): chronostratigraphy, deep crustal structure and tectonic evolution at the rear of a narrow slab rollback system. *J Geodynam* 77:186–205
- Michels K, Suckow A, Breitzke M, Kudrass H, Kottke B (2003) Sediment transport in the shelf canyon “Swatch of No Ground” (Bay of Bengal). *Deep Sea Res Part II Topic Stud Oceanogr* 50:1003–1022
- Miller K, Mountain G (1996) the Leg 150 Shipboard Party, and Members of the New Jersey Coastal Plain Drilling Project. 1996. Drilling and dating New Jersey Oligocene-Miocene sequences: Ice Volume, global sea level, and Exxon records. *Science* 271:1092–1095
- Mitchell NC (2005) Interpreting long-profiles of canyons in the USA Atlantic continental slope. *Mar Geol* 214:75–99
- Mitchell NC (2006) Morphologies of knickpoints in submarine canyons *GSA. Bulletin* 118:589–605
- Mountjoy JJ, Barnes PM, Pettinga JR (2009) Morphostructure and evolution of submarine canyons across an active margin: Cook Strait sector of the Hikurangi Margin, New Zealand. *Marine Geol* 260:45–68
- Mulder T, Savoye B, Syvitski J, Parize O (1997) Des courants de turbidité hyperpycniaux dans la tête du canyon du Var? Données hydrologiques et observations de terrain. *Oceanologica Acta* 20:607–626
- Nittrouer CA, Wright LD (1994) Transport of particles across continental shelves. *Rev Geophys* 32:85–113
- Normark WR, Carlson PR, Chan M, Archer A (2003) Giant submarine canyons: is size any clue to their importance in the rock record? *Special Papers-Geological Society of America*, 175–190
- O’connell S, Ryan WB, Normark W (1987) Modes of development of slope canyons and their relation to channel and levee features on the Ebro sediment apron, off-shore northeastern Spain. *Marine Petrol Geol* 4:308–319
- Orange DL, Breen NA (1992) The effects of fluid escape on accretionary wedges 2. Seepage force, slope failure, headless submarine canyons, and vents. *J Geophys Res Solid Earth* 97:9277–9295
- Orange D, Anderson R, Breen N (1994) Regular canyon spacing in the submarine environment: the link between hydrology and geomorphology. *GSA Today* 4:35–39
- Orange DL et al (1997) Headless submarine canyons and fluid flow on the toe of the Cascadia accretionary complex. *Basin Res* 9:303–312
- Popescu I, Lericolais G, Panin N, Normand A, Dinu C, Le Drezen E (2004) The Danube submarine canyon (Black Sea): morphology and sedimentary processes. *Marine Geol* 206:249–265
- Pratson LF, Coakley BJ (1996) A model for the headward erosion of submarine canyons induced by downslope-eroding sediment flows. *Geol Soc Am Bull* 108:225–234
- Pratson LF, Ryan WB, Mountain GS, Twichell DC (1994) Submarine canyon initiation by downslope-eroding sediment flows: evidence in late Cenozoic strata on the New Jersey continental slope. *Geol Soc Am Bull* 106:395–412
- Puig P, Palanques A, Martín J (2014) Contemporary sediment-transport processes in submarine canyons. *Ann Rev Marine Sci* 6:53–77
- Ratzov G, Cattaneo A, Babonneau N, Déverchère J, Yelles K, Bracene R, Courboulès F (2015) Holocene turbidites record earthquake supercycles at a slow-rate plate boundary. *Geology* 43(4):331–334
- Rouchy J-M, Taberner C, Peryt TM (2001) Sedimentary and diagenetic transitions between carbonates and evaporites. *Sed Geol* 1:1–8
- Scrutton R (1976) Crustal structure at the continental margin south of South Africa. *Geophys J Int* 44:601–623
- Shepard FP (1963) Thirty-five thousand years of sea-level Essays in marine geology in honor of KO. Emery 1:1–10
- Shepard FP (1981) Submarine canyons: multiple causes and long-time persistence. *AAPG Bull* 65:1062–1077
- Twichell DC, Roberts DG (1982) Morphology, distribution, and development of submarine canyons on the United States Atlantic continental slope between Hudson and Baltimore Canyons. *Geology* 10:408–412
- Twichell DC, Knebel HJ, Folger DW (1977) Delaware River: evidence for its former extension to Wilmington Submarine Canyon. *Science* 195:483–485
- Zaragosi S, Le Suave R, Bourillet J-F, Auffret G, Faugères J-C, Pujol C, Garlan T (2001) The deep-sea Armorican depositional system (Bay of Biscay), a multiple source, ramp model. *Geo-Marine Lett* 20:219–232