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Submarine canyon: A brief review

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ABSTRACT

Earth's surface configuration is in constant change due to geomorphic processes in operation. These processes are responsible for initiating several features such as channels, drainage basins, incised valleys, and submarine canyons. The understanding of these features is paramount for an accurate assessment of biological, environmental and geologic activities on land and in the sea. This article is a review of submarine canyons with overview of their geomorphic processes which discusses the origin, types and processes within canyons. Working with a compiled highly published materials of the world's most famous submarine canyons, this paper documents the historical evolution of the canyons over time and the different processes acting in the development of these canyons. From this study, the major factor controlling canyon creation is the seal level change. Turbiditic flow, and tectonics (faults and folds) favours canyon development. Canyon geometry can be both U-shaped, V-shaped or both depending on the tectonic or erosional influence. Although several works have been done on submarine canyon, the issue of submarine canyon evolution through time is minimal and accurate fluvial to canyon head connections are still a challenge. More focus on the stratigraphic and source to sink study of canyon systems can help give clue on the ages of canyons and the type of facies contained in it. This could be of benefit to the oil and gas industry in reservoir explorations.

Keywords: Submarine canyons, Reservoir, Evolution, Turbiditic current, Hyperpycnal flow

1.0: INTRODUCTION

Canyons, are erosional pathways, on land by fluvial erosion on uplifting continental plateaus (ex. Colorado) and tectonic barriers, or down to the deep-sea across the submarine shelves and slopes on both active (endogenetic) and passive (exogenetic) continental margins (Shepard, 1981; Brothers *et al.*, 2013). Since the pioneering study of Dana (1863), a large number of submarine canyons have been reported and studied on continental margins (Fig. 1).

The submarine canyons have been early related to the accumulation of transited sediments in deep sea fans (Fig. 2). Submarine canyons may be described as steep-walled cutting with V-shaped cross-sections that may exist down-slope to show a shallower U-shaped channel system (Daly, 1936; G. Lastras *et al.*, 2009). Authors have observed that submarine canyons are generated more on active margins than on passive margins; where canyons are steeper and closely spaced on active margins, sediment accumulation is higher on passive margin submarine canyons (Harris and Whiteway, 2011). Submarine canyon systems in plain-view, most times display tributary and follow a sinuous path (Lastras *et al.*, 2009; Huang *et al.*, 2014), though the values of sinuosity in average it is not seen to show a significant difference between active and passive margin canyons (Harris and Whiteway, 2011).

Erosion in canyon mostly operates through retrogressive sediment failures and active erosion by gravity movements (Mascle, 1976; Li *et al.*, 2013; Soulet *et al.*, 2016). The processes that transport deposit and further erode the underlying bedrock of submarine canyons are all reflected in the shapes of submarine canyons (Paull *et al*., 2018), depending on their size and duration. The presence of enormous sediment accumulation in deep basins from canyon heads in deep-sea turbidites and fans led Paull *et al*., (2013) to suggest that submarine canyons are priority conduits for sediment eroded from the continent and conveyed through large rivers (Puig, et al. 2014).

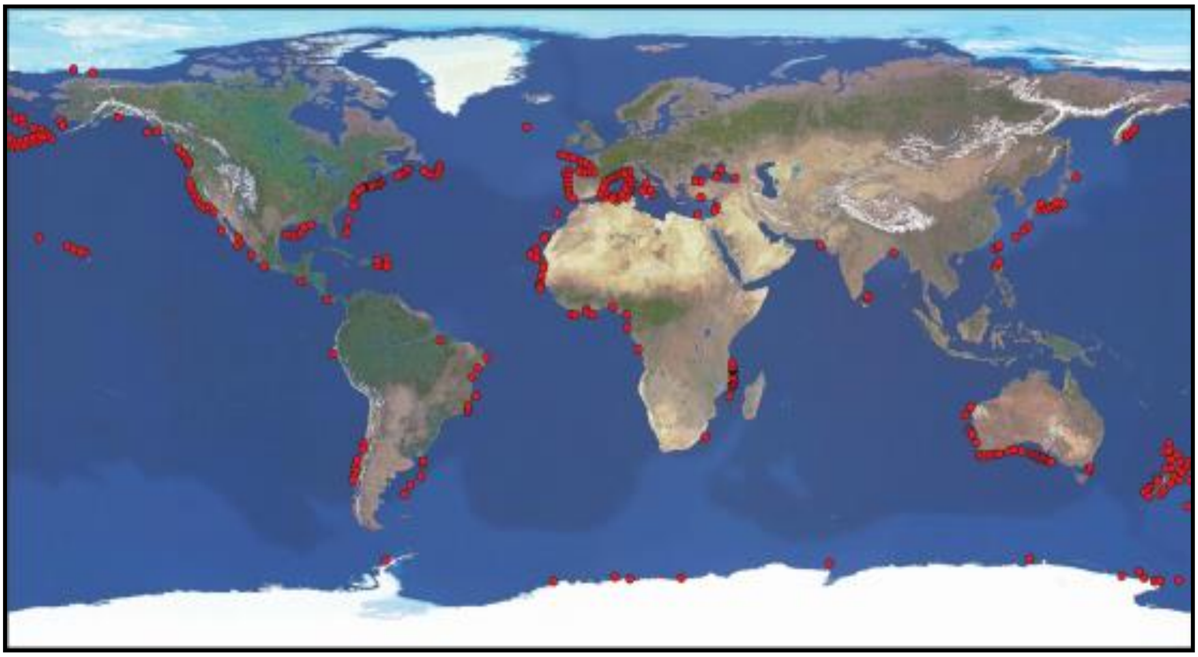

Fig. 1: Worldwide distribution of 660 submarine canyons (modified from De Leo et al., 2010). According to this map, approximately 35 submarine canyons exist in Africa

The morphology of submarine canyons is related to stratigraphic and structural activities. Although there has been a successful progression in the knowledge of modern submarine canyons (Palanques *et al*., 2006; Smith *et al*., 2007; G Lastras *et al*., 2009; Paull *et al*., 2013), explicit knowledge and understanding of the actual connection between coastal processes and the role of a submarine canyon in the transportation of fluvial sediment from the shelf environment to the deep basin remains poor.

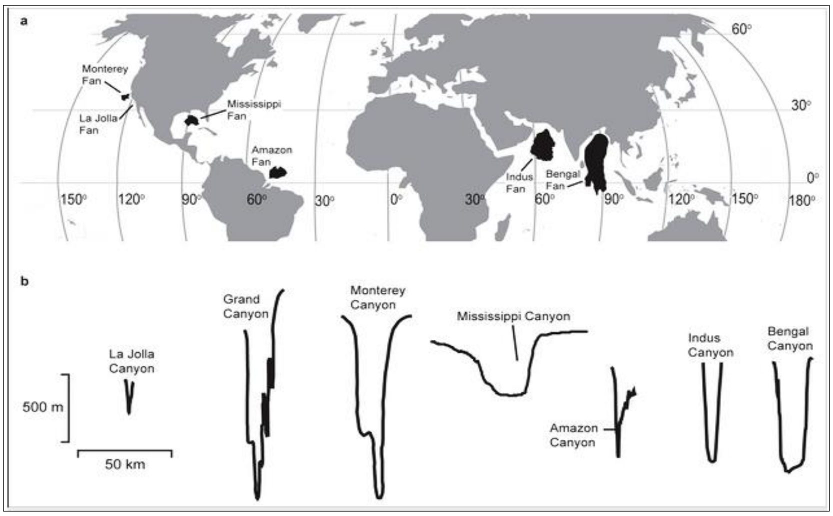

Fig. 2: (a) Location of some submarine fans (b) Submarine canyon profiles from Ryan et al. 2009.

2.0: TYPES OF SUBMARINE CANYONS

Authors have classified submarine canyons into two types, each using different names to organize the same canyons (Fig. 3). These two canyons are seen to exist on continental margins around the world and exist on both active and passive margins.

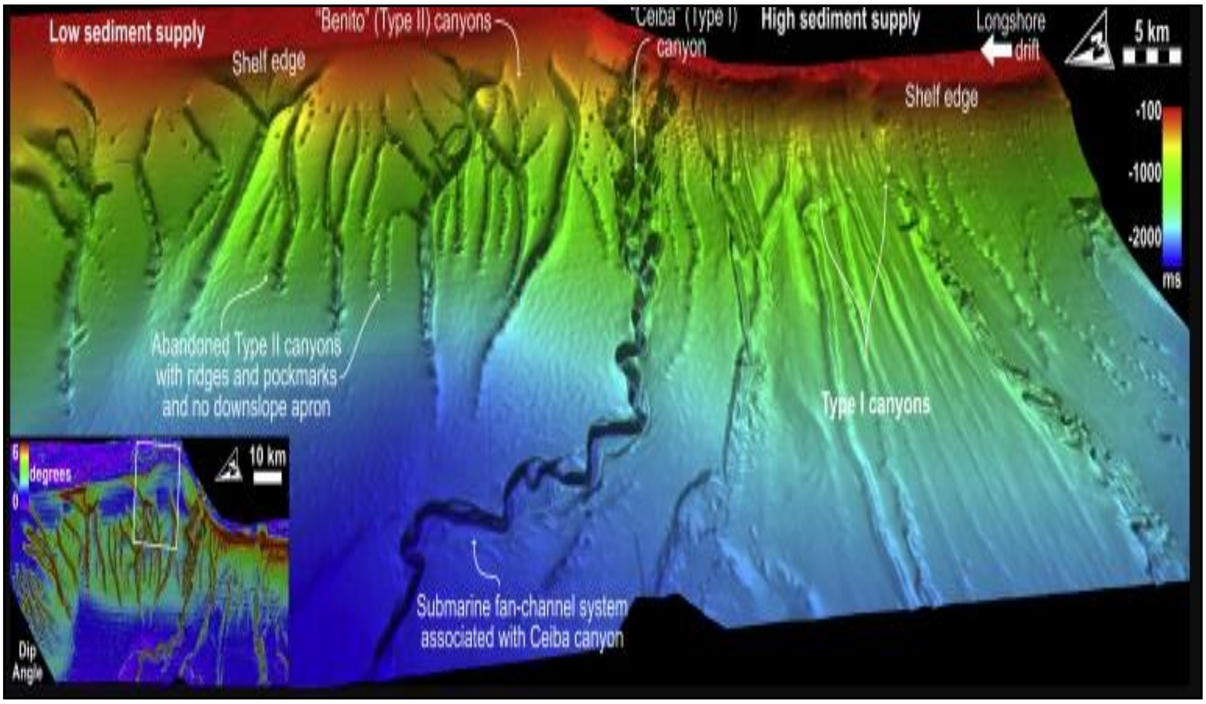

Fig. 3: Two types of canyons on the Equatoria Guinea margin. Type 1 canyon indents the shelf break and has a connection with the basin where it deposited submarine fans. Type II canyons are restricted to the slope environment without a link to the shelf or the basin area (Jobe et al. 2011).

Type I canyons (Jobe *et al.*, 2011) correspond to erosional canyons (Jobe *et al.*, 2011; Carter *et al.*, 2016; Soulet *et al.*, 2016) or shelf incised canyons (Farre *et al.*, 1983; Mauffrey *et al.*, 2017). Type I canyons have distinct geomorphic attribute of indenting the continental shelves (Fig. 4) of their existing environments. It has a direct connection between the continental shelf and the marine environment because its indentation of the shelf allows for a close association with the fluvial environments where sediments are quickly supplied and, through erosive submarine conduits, transferred to the deep basin. Erosional submarine canyons deposit turbidite, channel lobes, channel levee complexes, and contourite on the basin floors of ocean environments. They contain a series of channel complexes, levee complexes, and large mass transport complexes. The channels of the erosional submarine canyons are highly sinuous, and the canyon walls comprise scalloped features, which are believed to be due to canyon wall failures. With V-shaped cross-sectional geometry, its geometrical complexities are enormous, ranging from a dendritic head pattern to gully connections and even adjacent younger submarine canyon connections at several confluence points (Fig. 5). The presence of terraces in this canyon type depicts evidence of subsequent significant erosion and corresponding infilling regimes.

Type II canyons (Jobe *et al.*, 2011) are also called aggradational canyons (Soulet *et al.*, 2016), or slope canyons (Farre *et al.*, 1983), or slope confined canyons (Brothers *et al.*, 2013; Li *et al.*, 2016; Mauffrey *et al.*, 2017), or blind canyon (Harris and Baker, 2012), or headless canyon

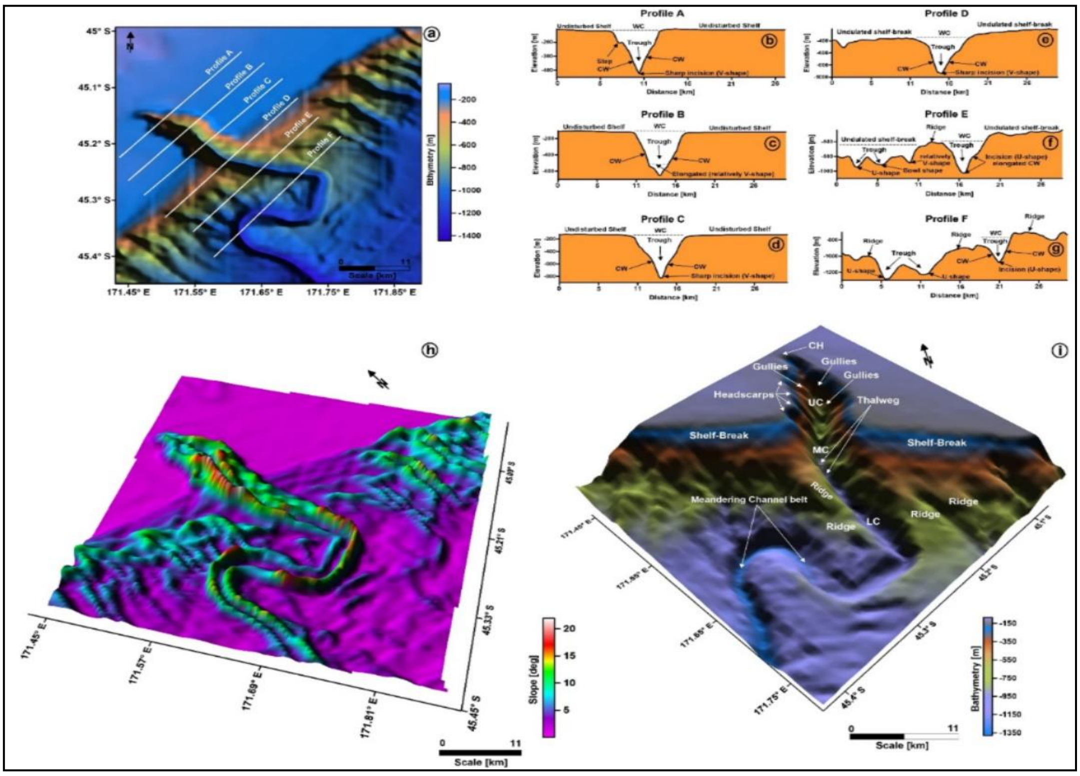

Fig. 4: Bathymetry map highlighting the geometry of the Waitaki Submarine Canyon at the shelf-break (adapted from Kumar et al, 2021)

(Harris and Baker, 2012). These canyons have no connection to the shelf environment nor the deep ocean environments because they are restricted to the slope regions, and their formation is generally attributed to structural activities such as faulting and folding. Also found in both passive and active continental margins, they are considered sediment-starved because of the disconnection from the near-fluvial environment. Most depositional canyon sediments are generated from wall failures within the submarine canyons.

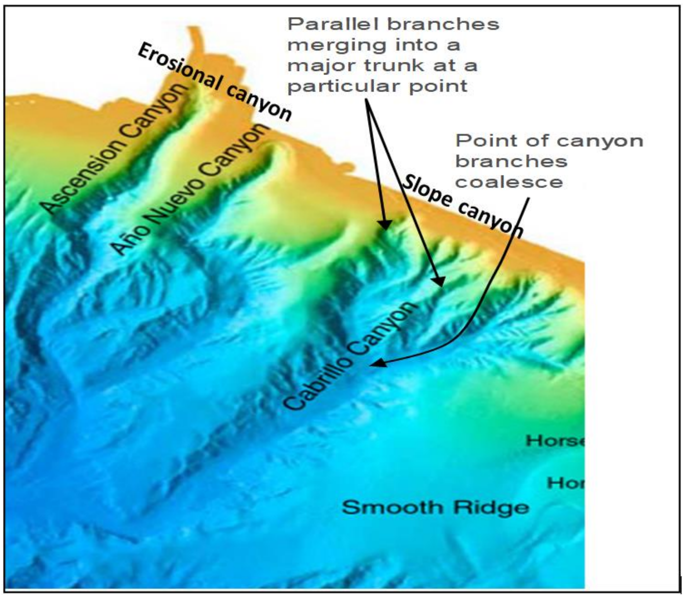

Fig. 5: Depositional submarine canyon reflecting incision of the continental slope with canyon head (slope canyon) restriction to the upper slope. This figure also shows activities of slope failure as it is made evident in the presence of mass transport complex (MTC) and slump deposits. With a thalweg of nearly straight part, this canyon type lacks channels and is with almost zero sinuosity. The entire canyon is located within the slope environment and without connection to the shelf or the deep ocean environment (Mbari, 2000).

3.0: ORIGIN OF SUBMARINE CANYONS

3.1: Historical insight

The study of canyons started in 1863 and was pioneered by Dana (1863). Since then, many publications on how submarine canyons are formed and evolve have been published. In his work, Shepard, (1936) continued exploration of California submarine canyon suggested that canyons are formed due to repeated emersion, erosion and infilling. He later studied canyons off New England and concluded that due to the height of the canyon walls, they could not possibly have formed from a single period of erosion. Daly (1936) and Kuenen (1938) had a similar discovery about the erosive power of marine turbidity currents. However, Daly (1936) was the first to suggest that turbidity currents erode submarine canyons. Shepard and Dill (1966), in their work, submarine canyons and valleys disagreed with Daly's hypothesis of marine turbidity current as a major player in canyon initiation. Instead, they support that rivers are responsible for the subaerial inception of many submarine canyons during relative sea-level low-stand. Almost a decade later, Shepard (1972) opposed his statement of rivers being the major influencing factor in canyon excavation and, from new evidence, supported Daly's idea of turbidity current being the chief initiator of deep water canyons. A few of his evidence are the locations of many canyon heads within the littoral zones away from vast river valleys. Examples are the Congo submarine canyon in Africa and the Monterey submarine canyon in Central California. Aloisi *et al.* (1975) noticed that subsequent occurrences of maximum sea-level falls were correlated to subaerial erosion with deep cuttings at the shelf edge and recharge of submarine canyons. Twichell and Roberts (1982) and Farre *et al.* (1983) not only support Daly's hypothesis on turbidity currents but also confirms Aloisi's claim that canyons are eroded by retrogressive mass wasting of the slope caused by sea-level fall. This statement conforms with the work of (Shepard 1981), where he postulated that submarine canyons evolve from slope erosion by mass wasting (slumping, landslide).

Furthermore, the belief that sediment gravity flows are the dominant canyon excavation procedure is supported by various observations (Kuenen, 1938; Shepard, 1981; Baztan *et al.*, 2005; Mitchell, 2005; Gerber *et al.*, 2009). Such sediment may start inside a canyon from local slope failure (Pratson and Coakley, 1996; Mitchell, 2005; Sultan *et al.*, 2007). However, various processes have been noted with the ability to create the downward movement of submarine canyons. These processes include hyperpycnal plunging (Mulder and Syvitski, 1995; Liu *et al.*, 2012); delta-front failure (Piper and Normark, 2009) & breaching (Talling *et al.*, 2015); wave re-suspension and shelf erosion related to waterfront/coastal storms (Parsons *et al.*, 2007; Sanchez-Vidal *et al.*, 2012) and dense shelf water cascading (Canals *et al.*, 2006). For the New Jersey continental slope, Pratson and Mountain proposed (Pratson et al., 1994; Pratson and Coakley, 1996; Mountain et al., 1983) a submarine canyon head-ward erosion model driven by downslope eroding sediment flows. This model was based on ideas from Daly, (1936) and Farre et al. (1983).

The influence of tectonics has been documented to play a role in creating submarine canyons. The work of Greene (1978) in Monterey Bay margin made a significant contribution to the study of the submarine canyon because it helped highlighting the active role of tectonics in submarine initiation. This work documented uplift, depressions, and right slip faults that offset major structural and lithologic elements. These deformations created several unconformities and initiated the development of submarine canyons that today comprise the Monterey, Carmel, Ascension, and several other canyons. Nagel *et al.* (1986) finding supports Green's hypothesis that tectonic truncation and lateral displacement can produce submarine canyons along strike-slip-dominated continental margins.

Some authors even argued that fluid seepage is an actor in submarine canyon initiation. For example, Orange and Breen (1992) and Orange *et al.* (1994) attributed the origin of blind/slope submarine canyons to fluid seepage-induced slope failure. Greene *et al.* (1999) and McAdoo *et al.* (2000) also attributed the formation of the deepwater canyon to submarine seeps. Another example is Benito canyon off the Equatorial Guinean coasts (Jobe *et al.*, 2011) or along the eastern margin of Japan, where pockmarks formed by hydrostatic pressure release during sea-level falls might have initiated canyon development (Nakajima *et al.*, 2014).

In his elaborative submarine canyon review, Shepard (1981) stated that most submarine canyons might originate due to composite processes acting over long periods of geologic time, interrupted by intervals of erosion or condensation. A typical example is the east coast of South Africa which was related to several phases of hinterland uplift at the origin of the incisions of Tugela Canyon. This process was superseded by hemipelagic filling and reworking by deep ocean currents (Wiles *et al.*, 2013). Another example is the Bay of Biscay, where the Capbreton submarine canyon incised the large shelf of Aquitane, showing a highly sinuous pattern followed by an axial incision documented to have emanated when the canyon head had a direct link with a river (Baztan *et al.*, 2005). However, recent studies into this canyon by (Mazières *et al.*, 2014) emphasized that it underwent sedimentological and morphological growth due to the massive transportation of sand eroded from the coastal environment during a high flood. Indeed, the above statements depict that submarine canyons are developed in most cases by the combination of fluvial and marine processes.

3.2: Fluvial erosion during Sea-level Low stands

Subaerial erosion is a necessary process and one of the factors in submarine canyon evolution. Shepard (1936) hypothesized that submarine erosion is the major canyon initiating process. He came up with this after disputing Davis and Daly's hypotheses of submarine current and cut by heavy mudflow, respectively. During the last glacial maximum, most shelves were subaerially exposed when the global eustatic sea level was approximately 120 m below its present position causing rivers to prograde basinward towards the exposed shelf, creating incision across what is today the continental shelf (Fig. 6).

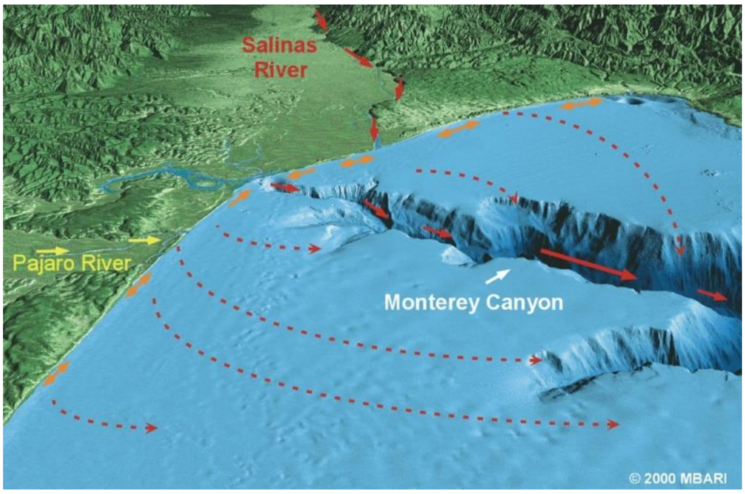

Fig. 6: Example of Monterey Canyon showing the close connection to a river that flowed into the canyon during lowstands of sea level (Mbari, 2000)

The transportation of sediments to the shelf break during the last glacial maximum in the Pleistocene ice ages gave a sediment source to downward turbidity flow and canyon excavation. This process occurred only in a couple of submarine canyons during the glacial sea level high. An example is Congo canyon in Africa, described by Shepard and Emery in Shepard (1941) and a significantly major river in Papua New Guinea, depicted by (Kineke *et al.*, 1996). The evolution of virtually all submarine canyons and their associated fluvial features have been attributed to eustatic sea-level fluctuation (Twichell and Roberts, 1982; Farre *et al.*, 1983; Nagel *et al.*, 1986; Pratson *et al.*, 1994; Mountain *et al.*, 1996; Pratson and Coakley, 1996; Algan *et al.*, 2002; Su *et al.*, 2019). This is because relative sea-level low stand impacts the connection between fluvial processes and the shelf break and create specific terraces in the shelf catchment (Fig. 7).

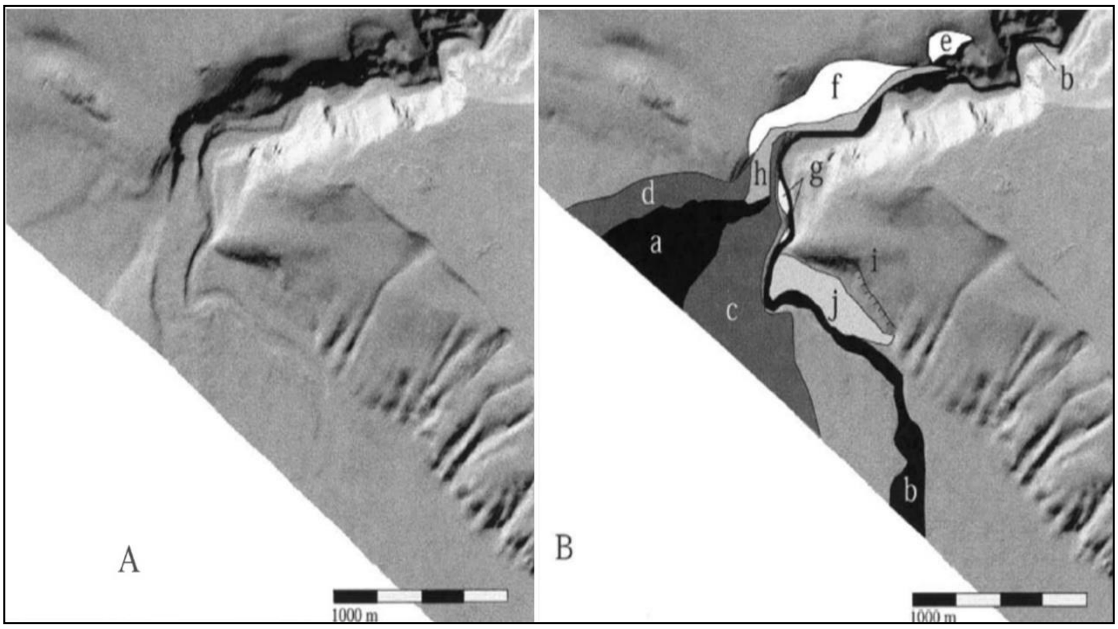

Fig. 7: (A) Plan view of shaded relief of mouth of Redondo Canyon. (B) Interpretation shown by overlays: (a) blocked outlet channel; (b) active outlet channel; (c) and (d) levees; (e) and (f) failures of north wall; (g) failures of levee c; (h) terrace along a north wall; (i) head scarp of basin slope failure; (j) debris pile from basin slope failure that diverted channel (Gardner et al, 2003).

Most submarine canyons formed due to this process have their heads on the upper slope or indent the shelf with a few meters. However, after that, if the canyon head grows retrogressively, it gets closer and captures fluvial sediments and serves as a transportation medium to the deep basins. Subsequent occurrence of sea-level fall could create excavation that gradually develops into submarine canyons (Aloisi *et al.*, 1975).

3.3: Tectonic activity

The complex erosional and depositional history of numerous submarine canyons (Niger delta submarine canyons, Ascension canyon, and South China sea submarine canyon) around the world owe to tectonic uplift or faulting (Mascle, 1976; Nagel, et al. 1986; Cohen and Mcclay, 1996; Algan *et al.*, 2002; Shanmugam, 2002; Li *et al.*, 2013; Fig. 8). Damuth (1994) suggested that deformation by gravity tectonics may affect the evolution, location, and longevity of the submarine canyon (Fig. 8). Damuth (1994) postulated that shale diapirs might be the reason why most large canyons were short-lived and, in return, fed the adjacent intraslope basin.

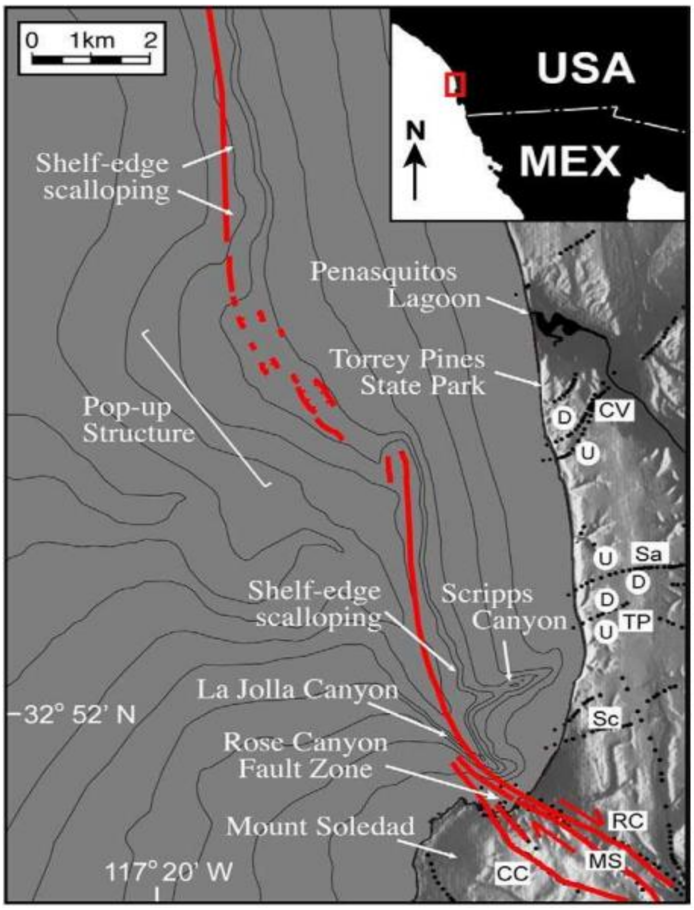

Fig. 8: Southern California canyons showing the left jog along the right-lateral Rose Canyon Fault and the consequent structural high on the inner shelf (Dartnell et al., 2007).

4: SUBMARINE CANYONS PROCESSES

Suspension deposits dominate in the sedimentary record of submarine canyons (Gorsline, 1970; Carson *et al.*, 1986; Gardner, 1989; Palanques *et al.*, 2006), based on studies of suspended particle flows (Hung and Chung, 1998; Puig and Palanques, 1998) or sediment concentration rates (Carson *et al.*, 1986; Lastras *et al.*, 2009; Liu *et al.*, 2009; Amblas *et al.*, 2018), which are both higher than the open slope environment (Puig *et al.*, 2003), yet mediums involved in moving sediments into and through submarine canyons are not entirely comprehended (Micallef *et al.*, 2014). Since the 1950s, there has been progressing in understanding sedimentary processes in deep ocean canyons and channel frameworks because of both field studies and modelling studies of the causes and methods of sediment flow in the surrounding environments (Shepard and Buffington, 1968). Perhaps the most noteworthy development in understanding submarine sediment transport forms originated from the advancement of oceanographic instrumentation in the late 1960s that could remain conveyed for extended periods (Micallef *et al.*, 2014). Progress in the investigation of submarine canyon processes has additionally advanced with the capacity to gather point-by-point bathymetric information to record ocean bottom morphology (Paull *et al.*, 2013). For instance, besides the fact that suspension dominates, strong tractive currents are found almost everywhere to maintain large sandy bedforms as the crescent-shaped dunes of the axial channel of Monterey Canyon (Xu *et al.*, 2008; Symons *et al.*, 2016). The next sections provide elements about the hydrodynamics and sedimentary processes in submarine canyons.

4.1: Mass wasting

The concept of mass wasting is related to the deformation processes taking place on the slope. This failure may evolve through the retrogressive movement of the already excavated submarine canyon with the possible chance to capture fluvial systems. The above scenario was rooted in the observations made by Twichell and Roberts (1982), where he emphatically stated that submarine canyons might cut across the shelf edge, whereas some others may be confined to the slope. They further suggested that the former developed through headward erosion of the latter type. This suggestion was supported and developed by Farre *et al.* (1983), who proposed a situation with a primary stage dominated by slope failures (Fig. 9), followed by the development of turbiditic flows supplied by seaward sands after the canyon head arrives at the shelf edge. The Yoakum/Lavaca submarine canyon in the Gulf of Mexico, the Andya canyon in the Norwegian Sea, or the Bari canyon in the Adriatic Ocean all lack a connection to any river system. This "base up" scenario has been used to explain their origins. According to this theory, late Miocene submarine canyons in the South China Sea originated through headward retrogressive erosion that was accelerated by high contour currents, as was also seen on the Argentine continental margin (Lastras et al., 2011; Li et al., 2013).

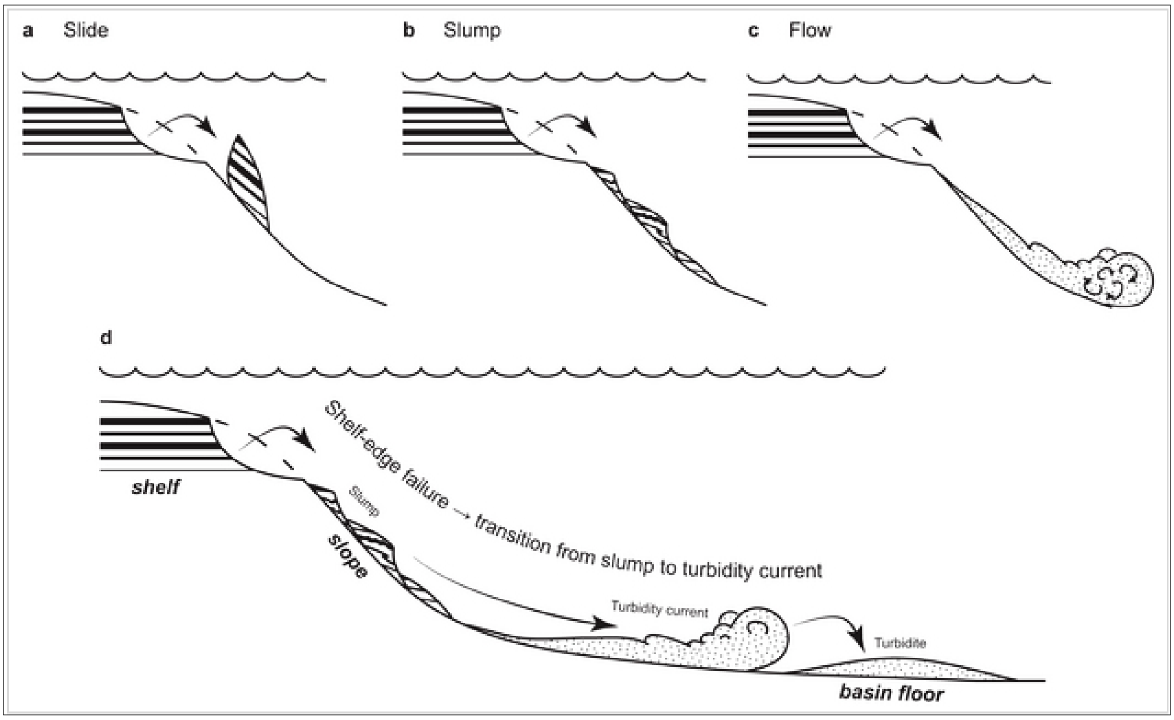

Fig. 9: (a-c) Types of submarine mass movements, which generally are distinguished based on degree of internal deformation. (d) Initiation of a submarine mass movement as a result of shelf-edge sediment failure, followed by transformation from slumping to turbidity-current processes. From Middleton & Hampton (1973).

4.2: Slope failure to debris flows

As stated earlier, Daly (1936) was the first to hypothesize the idea of turbidity currents as the main factor in the development and erosion of submarine canyons. Turbiditic currents (Fig. 9) are initiated by mass-failure, commonly caused by overload at the shelf edge (Pratson *et al.*, 1994), or hyperpycnal flows triggered by river floods (Mulder et al., 2003; Piper and Normark, 2009). In his work on the Gulf of Lions (Baztan et al. 2005), Baztan hypothesised that the relationship between some canyon heads' fluvial systems during the Last Glacial Maximum period led to the construction of narrow (300 m wide) axial incisions that were approximately 100 m deep, incising the thalweg of the major canyons. Turbiditic flows would remove sediments collapsed from the canyon walls, allowing the enlargement of the submarine canyon through time (Sultan *et al.*, 2007).

Debris flows are derived from submarine slope failure and form mass-transport deposits that progressively pass downslope to chaotic or sheet deposits (Shepard, 1981; Arzola *et al.*, 2008; Brothers *et al.*, 2013; Fig. 10) and are known to be cohesive (Mulder and Alexander, 2001). The principle support mechanism in debris flow movement is reduced particle density, the yield quality of the sediment-water mix, and particle grains collision (Iverson, 1997; Talling, 2014). Though debris flows are correlated to weak turbulence, they are generally laminar (Iverson, 1997; Peter j. Talling, 2014). Deposition from debris flows called "debrite" is often very fast, resulting in poorly sorted, ungraded, and structureless deposits (Lowe, 1982; Mulder and Alexander, 2001).

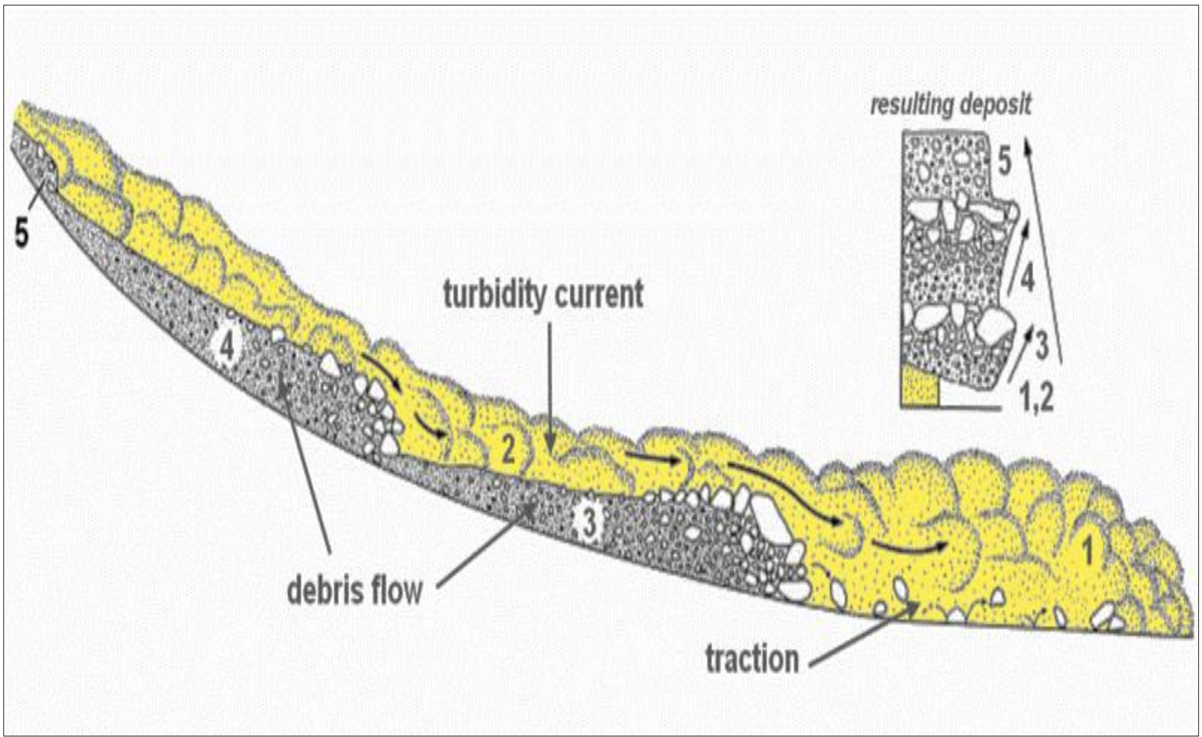

Fig. 10: *Diagram showing debris flow, turbidity current and traction processes operating in a sediment gravity flow. Modified from Young K. Sohn (2000).*

4.3: Turbidity Currents

The present belief is that turbidity current flows are the predominant mode for moving sediments through submarine canyons (Shanmugam, 2000; Paull *et al.*, 2011). Turbiditic flows are sediment-gravity flows with Newtonian rheology, and a turbulent state where sediment is assisted by fluid turbulence and deposition occurs through suspension settling (Shanmugam, 2006). The Newtonian rheology makes turbidity current deform and move upon the initial application of shear stress, and their driving force mechanism is the differential weight between the cloud of suspended sediment and the ambient water (Meiburg and Kneller, 2010). The range of sediment concentration in turbidity current is between 0.1% to 7%.

4.4: Hyperpycnal Flows

Hyperpycnal flows are turbid water plumes that can plunge to create turbidity currents where they enter less-density water (Lamb and Mohrig, 2009). They occur at a river mouth during a flood of little to medium-sized streams or rivers. Related to high-suspended concentration, they can ship a significant volume of sediment to the deep basin (Fig. 11). The regular hyperpycnal deposit succession is a compound of a basal coarsening-up unit during the waxing time of discharge and a top fining-up unit saved during the fading time of discharge (Mulder *et al.*, 2003). Hyperpycnal flow has been noted as one of the most direct links between fluvial sediment sources and marine depositional basins (Lamb and Mohrig, 2009). Contingent upon the grain size of suspended materials, hyperpycnal flows can be muddy or sandy. Sandy hyperpycnal flow can convey bedload bringing about sandy to gravel composite beds with sharp to progressive internal facies (Zavala and Pan, 2018). Hyperpycnites differ from other turbidites because of their intra-sequence erosional contact and well-formed inversely graded facies. Hyperpycnal flow could likewise be connected with the formation of meandering canyons and channels (Mulder *et al.*, 2003).

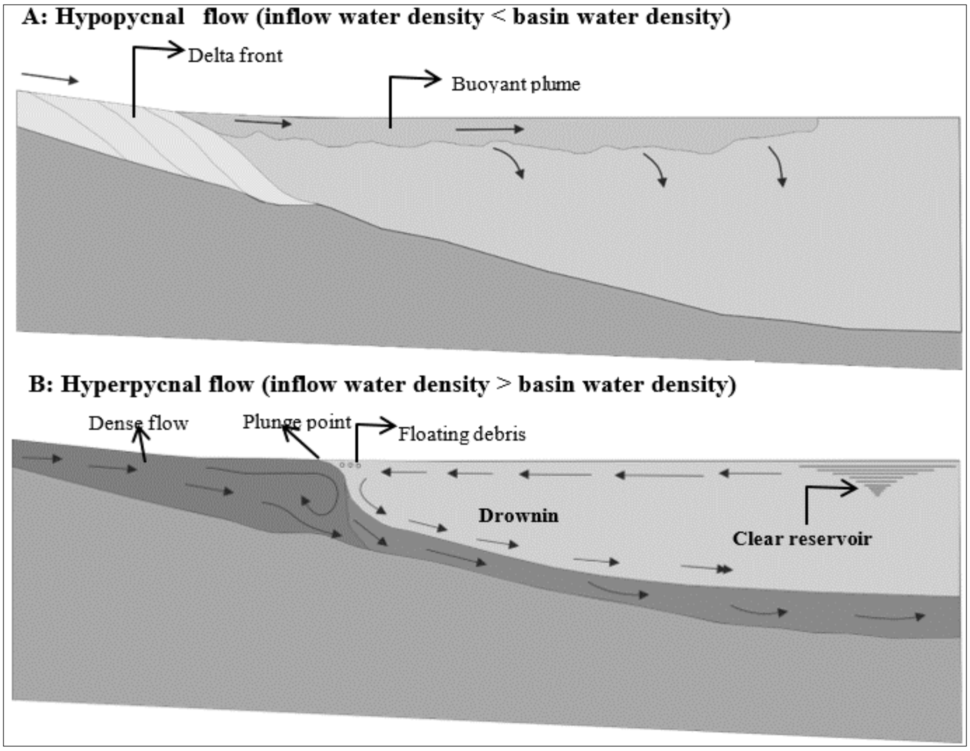

Fig. 11: Comparison between hypopycnal (A, inflow density < sea-water density) and hyperpycnal (B, inflow density > sea-water density) flow (original concept by Bates, 1953). Panel B was re-drawn. In the case of the hyperpycnal flow, the fluvial discharge sinks below the sea-water body, continuing its travel basinward as a quasi-steady underflow. After Zavala et al. (2008).

4.5: Littoral Drift

Apart from the direct sediment delivery from rivers to the submarine canyon heads, littoral drift or longshore current can also serve as the primary source of sediment transport in the canyon heads when there is a narrow continental shelf or the absence of a shelf entirely (Shepard, 1972; Shepard and Dill, 1966). This phenomenon is the case with Lopez Canyon, Biscara et al. (2013), and on the Californian margin with the La Jolla canyon (Covault et al., 2007). In this situation, however, sediment transfer is practically through several gullies or valleys; canyons whose heads are close to the coast can also capture longshore drift sediment (Canals et al., 2006; Lastras et al., 2007).

4.6: Shelf Water Cascading

Dense shelf-water cascading is a meteorologically driven oceanographic process where dense water generated by cooling, evaporation, or freezing above the continental shelf flows down the continental slope to a considerable depth as a gravity-driven current (Lastras *et al*., 2007). Dense shelf water cascading (DSWC) can ship sand and make high sediment transitions inside a submarine canyon (Canals *et al*., 2006; DeGeest *et al*., 2008; Heerema *et al*., 2020). This meteorologically determined oceanographic process comes about because of the cooling or evaporation of shelf water (Fig. 12). The dense water overflows the shelf edge and falls downslope as a gravity-driven current until it reaches an equilibrium depth (Canals *et al*., 2006; Puig, 2014). These cascading occurrences can be increased by cold, dry wind, which cools and homogenizes the shelf water section, encouraging dense water development (Palanques, *et al*., 2006). These low sediment concentration streams/flow can go on for quite a long time, from days to several weeks, while at velocities of up to 85 cm/s (Canals *et al*., 2006; Peter J. Talling, 2014).

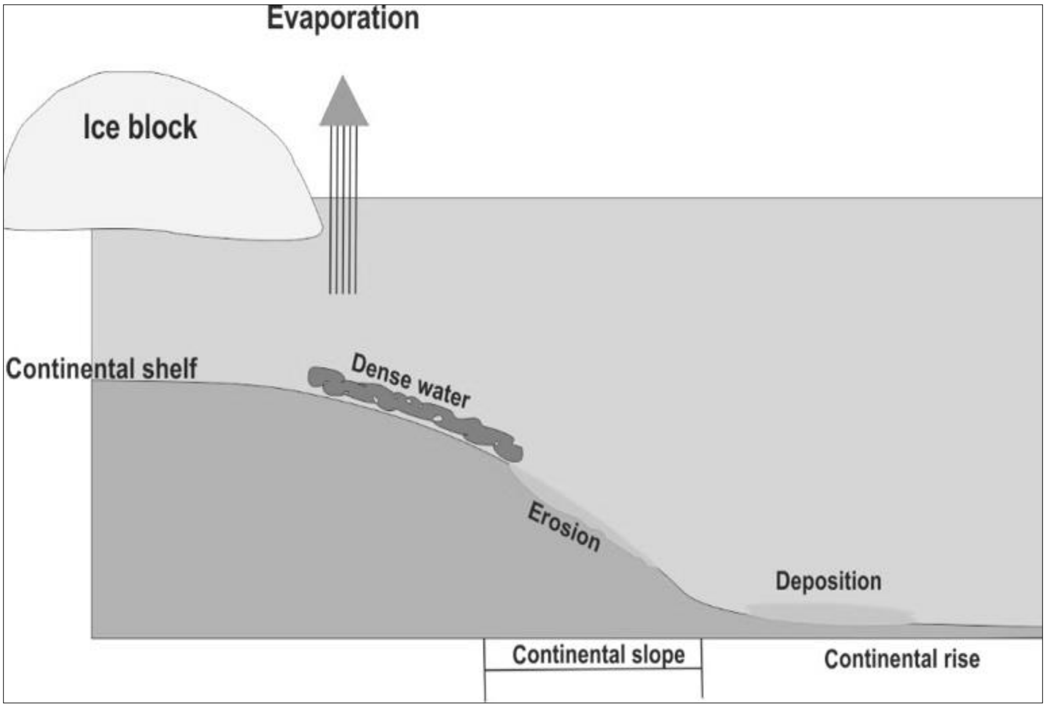

Fig. 12: Dense shelf water cascading processes in sediment transportation (NOAA).

4.7: Oceanic Tides

Submarine canyons influence the development of water masses horizontally along continental margins and vertically inside submarine canyons, as is the case for baroclinic or internal tides. For an extended period, the Coriolis effect may interplay, and it has been established that those combined effects can control the location of erosion, the overall asymmetry of the canyon and construction of drifts at its outlet (Petruncio et al., 1998).

5.0: SUBMARINE CANYON MORPHOLOGY

Canyon morphology relies upon the sediment deposition pattern that drives prolonged outbuilding of continental margins (Gerber *et al.*, 2009), although the long-term maintenance of canyons is poorly understood (Lo Iacono *et al.*, 2014). Considering the geomorphic and geometrical differences between a wide range of submarine canyons located in various geological settings, the processes responsible for the excavation shaping and development of submarine canyons are summarized in terms of up-down and down-up processes (Shepard, 1981; Twichell and Roberts, 1982). The up-down processes refer to hyperpycnal flows and turbidity currents occurring along the shelf margin, which creates axial incision (Fig. 13) from upper regions down to the slope in varying erosive and depositional architecture (Baztan *et al.*, 2005).

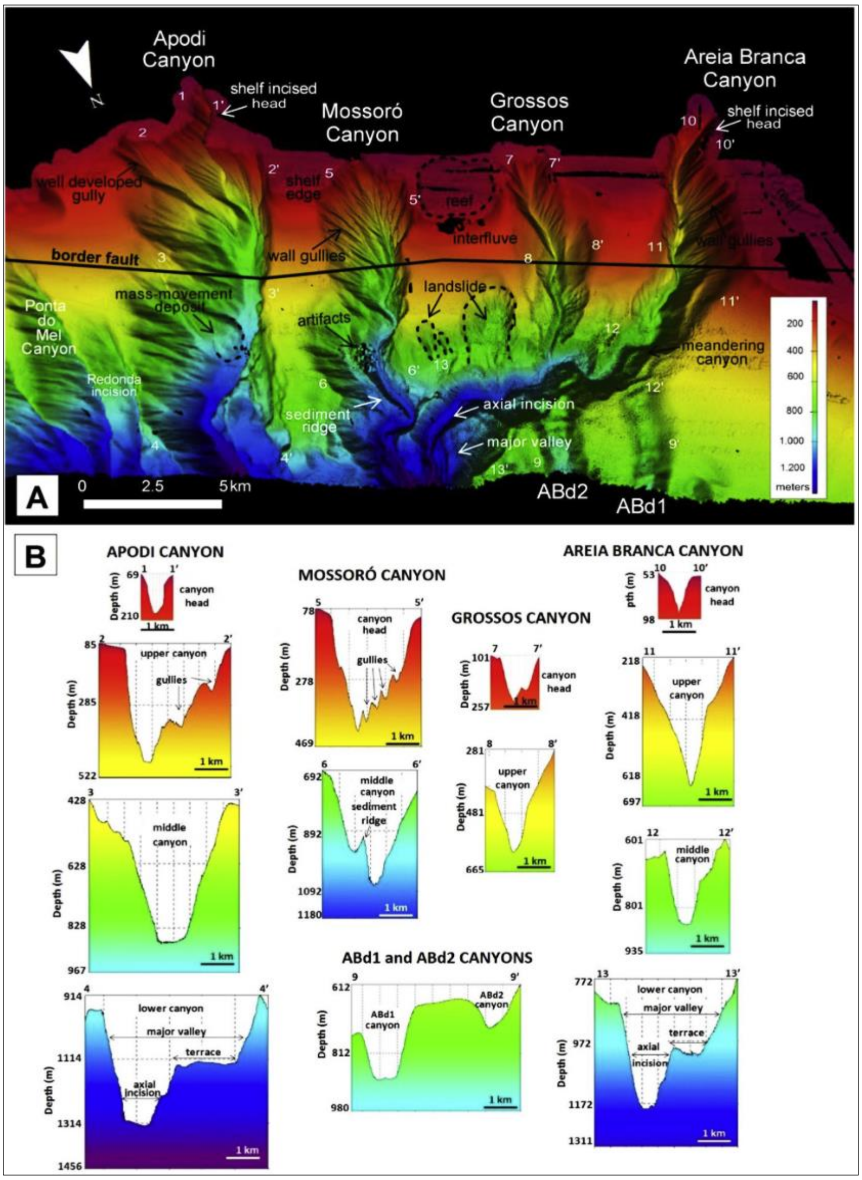

Fig. 13: A) Morphobathymetric map of submarine canyons (Vertical exaggeration: ~10) showing the V and U-shaped canyon geometry, terraces, gullies, landslides and canyon heads. B) Cross-sectional profiles of the canyons (ABd1 and ABd2 ¼ distributaries of Areia Branca Canyon. Seabed morphological features are interpreted. From Almeida et al. (2015).

These up-down processes seemingly always occur in moderate to high sediment supply continental margins, fed by onshore (fluvial and coastal) sedimentary inputs and are noticed to be active mainly during the glacial period (Baztan et al., 2005; Canals et al., 2006; Harris and Whiteway, 2011; Fig. 14). The down-up processes are developed by slope wall failure accompanied by stacked mass movement transgressing from the lower slope environments to the shelf break domain; these processes usually are active in a sediment-starved area, in a tectonically active and highly steep continental slope (Lo Iacono et al., 2011; Biscara et al., 2013; Micallef et al., 2014). The two processes (up-down and down-up) are mechanisms at the forefront of canyon shaping and development. The up-down turbidity process excavates an axial incision that leaves an erosive and highly sinuous channel imprint from the shelf. On the other hand, the down-up progress in headward erosion produces debris flows and mass wasting while widening canyon width (Pratson and Coakley, 1996; Lo Iacono et al., 2011). According to Twichell and Robert (1982), canyons range from straight to sinuous; the canyons with sinuous axes created by up-down mechanism cut the shelf-break (Twichell and Robert 1982) and are often older than the upper slope canyons while the down-up mechanisms create the linear axes submarine canyon and appear to be younger than the shelf indenting canyons (Twichell and Robert 1982).

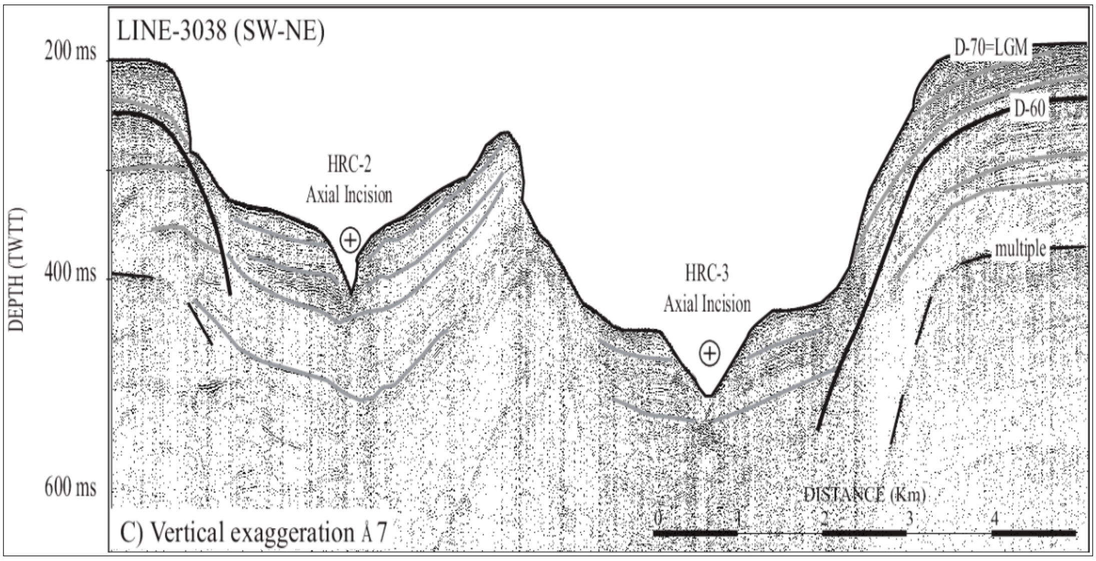

Fig. 14: Seismic line across the upper reaches of the Herault canyon in the Gulf of Lion (France). From Baztan et al. (2004).

CONCLUSION

Submarine canyons are formed from the combination of fluvial and marine processes. The detailed understanding of their geomorphic attributes can help decipher the genesis and processes that operated in the time past. They are important in understanding the deep-sea sedimentation process, and sediments within the canyon are primarily transported through turbidity current flow and littoral drift. The processes responsible for the excavation and shaping of submarine canyons is summarized as the up-down and down-up processes (canyon initiation and subsequent development). Although, there has been a successful progression in the knowledge of modern submarine canyons, explicit knowledge and understanding of the actual connection between coastal processes and the role of a submarine canyon in the transportation of fluvial sediment from the shelf environment to the deep basin remains poor, and stratigraphic evolution of canyon study is recommended.

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