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ON THE ORIGIN OF SUBMARINE CANYONS

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ABSTRACT

It is suggested that the origin of submarine canyons depends on two factors:

1. a drop of the ocean level below the shelf/slope rim as a consequence of the formation of enormous ice masses during a glaciation.
2. the presence of powerful streams, created by the melting of ice masses; these streams carried large amounts of glacial debris across the shelf and deposited them on the continental slope.

Continuous overloading of these debris piles resulted in debris avalanches downslope, which excavated canyons and ultimately formed large submarine fans.

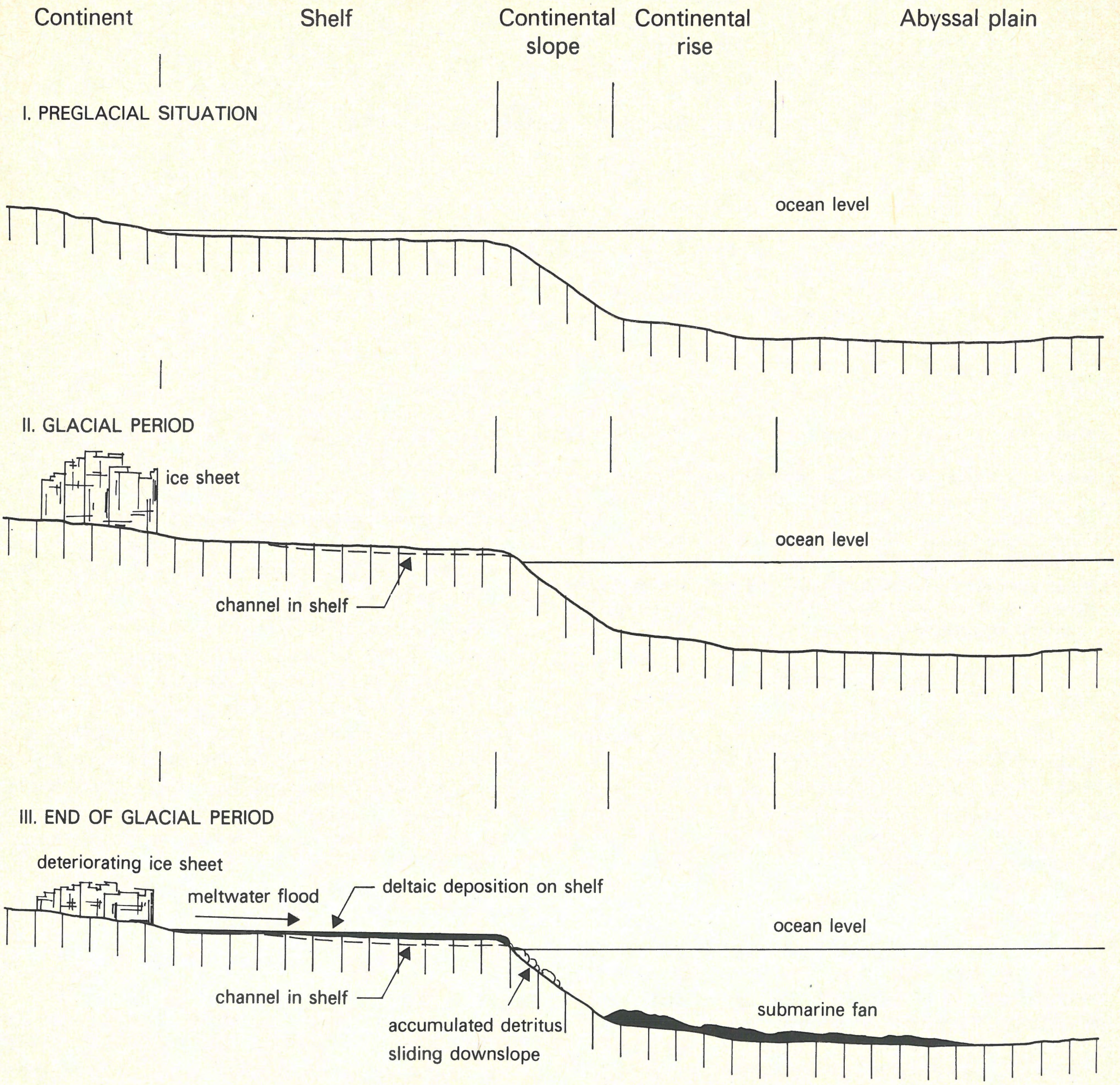
INTRODUCTION

It is a little over a hundred years ago that Dana (1863) first discussed the valley off the Hudson estuary. There was, however, little interest in submarine canyons until more of these were discovered and contour maps appeared. Many geologists refused to take the "seavalleys" seriously and it was not until the adoption of echosounding and the production of series of profiles by the US Coast and Geodetic Servey that their attitude changed. Numerous hypotheses were submitted. Johnson (1939) suggested that *artesian springs* had excavated the canyons. This hypothesis was never well documented and reflection profiling eliminated the concept. Bucher (1940) put forward the *tsunami* hypothesis, but it found no support in field studies. Lawson (1893) and Wegener (1924) thought they could explain submarine valleys as *fault valleys*. Submarine canyons, however, extend across the continental slope, they do not follow the structural trends of the adjacent continent, have sinuous axes and cut right through fault barriers. The fact that the pattern of the submarine canyon with its dendritic tributary system closely resembles that of a river, presented the argument for ascribing the same origin to both: thus the *drowned river* hypothesis was born. As a general concept this hypothesis appears unacceptable. Many canyons have been traced to a depth of 3 000 meters, while the average maximum depth is around 2 000 meters. The submergence of all coasts with submarine canyons to depths of 2 000 meters or more is too unlikely to accept. Kuenen (1953) assumes that *turbidity currents* result from the slumping of accumulations of sediment along a break in slope. An avalanche may be triggered by seismic shock or an oversteepening of the sedimentary gradient. The sliding masses are thrown into suspension and flow down the slope. On a nearly flat surface, however, such a suspension spreads out, loses momentum and dissipates (Buffington 1961). On a steeper slope it flows more or less straight down and shows few, if any, tributaries. There are more objections to the concept that turbidity currents are a major cause of the excavation of submarine canyons.

1. The sediment which formed the suspension was ultimately deposited at the canyon mouth as a submarine fan. The volume of the fan of a single canyon can amount to tens of thousands of cubic kilometers. It contains mud, sand, gravel, cobbles and sometimes even rounded boulders. It is hard to see how this enormous amount of sediment could first accumulate at a break in slope and then be converted into sluggish turbidity currents which were accurately funnelled into a mutual channel to erode V-shaped gorges in hard rock.
2. It has been suggested that sand transported by longshore drift and intercepted at a canyon head, could well excavate canyons. It is argued that the upper part of the canyon provides the steep gradient and the restricted channel favourable for the conversion of sediment slides into turbidity currents. Although longshore drift is doubtlessly capable of moving enormous quantities of sand, the presence of a steep gradient is mentioned as a prerequisite for turning a sand accumulation into a turbidity current. How this pre-turbidity gradient came into being is not clear. Turbidity currents are still active in Congo Canyon, where they often cause cable breaks. It is not possible to ascribe these to the result of longshore drift as the essential canyon head is situated 25 kilometers inside the coastline. The existence of parallel canyons poses another problem for the longshore drift concept. Of two parallel depressions one is apt to capture most of the sand supply, which implies a poor development of the second canyon.

Analysis of the current hypotheses leads to the conclusion that none of the concepts provides a satisfactory explanation for some of the phenomena observed in submarine canyons and their fan valleys.

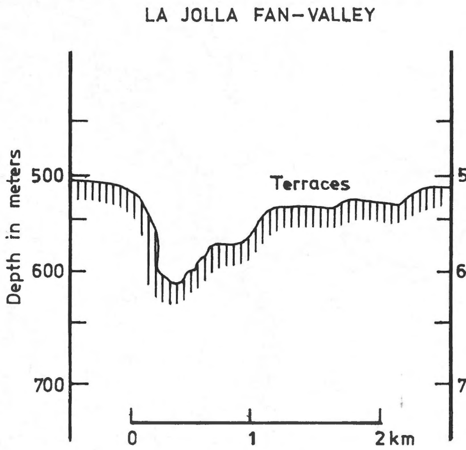
1. In an article on La Jolla submarine fan by Shepard et



Deltaic deposition on shelf built by meltwater floods with high content of debris spilling over channel banks.
Main river channel deposition detritus on slope. Overloaded pile of accumulations slides downslope, eroding canyon.

al. (1969) a core (fig. 15, p. 402) shows plant debris (kelp, surfgrass, wood, etc.) underlain by a semi-consolidated... clay. Deeper: coarse sand, gravel, shells, mudballs, etc.... and finally layers showing bioturbation by burrowing organisms.

Griggs and Kulm (1970) report a case from the Cascadia Channel: "Above a coarse, basal zone and sharply separated from it (lies) a homogeneous... much thicker bed consisting of silty clay." More of these pseudo-unconformities are described by Piper and Normack (1971) and Hand and Emery (1963). The latter authors mention that in the San Diego trough "below 200 centimeters of hemi-pelagic silt coarse turbidite material occurs in a nearly uninterrupted series of thick graded beds. Ericson (1952) describes two cores from the gorge of the Hudson fan-valley as "a confused mixture of



Adapted from Shepard - Dill (1966)

Fig. 2

gravel, cobbles and shells with a mud matrix." Richards and Ruhle (1955) found these cores to contain shells of a "shallow water species mixed with species of moderate depth".

2. From the concepts proposed it is not clear what type of flow built the huge fans at the mouth of the canyons. Menard (1955) pointed out that the large number and great length of the deepsea channels show that a significant proportion of the turbidity current flow did not occur in the form of sheet flow. Griggs and Kulm (1970) mention that 750 kilometers from shore coarse sand and gravel were found. In La Jolla fan-valley Shepard and Dill (1966) observed rounded boulders with a diameter of nearly one meter. Quite some fan-valleys show evidence of the height of enormous floods that passed through.

Source	Location	Height of flood (m)
Griggs and Kulm (1970)	Cascadia deepsea channel	127
Shepard and Dill (1966)	La Jolla fan-valley	180
Hand and Emery (1963)	San Diego trough	Coarse sediments on shelves and banktops of levees of fan-channel

3. Other sources underline the evidence of strong erosion definitely not caused by creeplike flow of sand bodies.
   a. Canyons heading on a wide continental shelf cut into the self over distances of more than 30 kilometers.
   b. Submarine canyons often show V-shaped transverse profiles cut into hard rock.
   c. The walls along the channel through the fan valley often show extra-ordinary steepness (70 to 80 degrees). Shepard and Dill attribute them to recent erosion. Hand and Emery write: "Erosional capability (of turbidity currents) is demonstrated by the terracing of the walls of the fan-valley." (fig. 2)

The phenomena outlined above all point to the existence of turbidity floods of great power and magnitude. Kuenen who always strongly supported the turbidity current concept, must have recognised this as he wrote (1968) "... turbidity currents carried shallow, benthonic organisms... and thick shells or pebbles over distances of hundreds of kilometers across plains at 5 000 meters depth."

A HYPOTHESIS

It is suggested that the excavation of submarine canyons is attributable to the periods that witnessed the deposition of large volumes of debris on the continental slope which had been bared as a result of the formation of gigantic ice sheets.

At the onset of a glaciation the North Canadian nucleus of an ice sheet expanded rapidly as a result of extensive precipitation, nourished by maritime evaporation. The ever growing ice masses had a general cooling effect on the atmosphere which was favourable to further expansion of the continental ice sheet. As the ocean level dropped steadily, baring the continental shelf, the existing rivers extended their beds towards the retreating ocean.

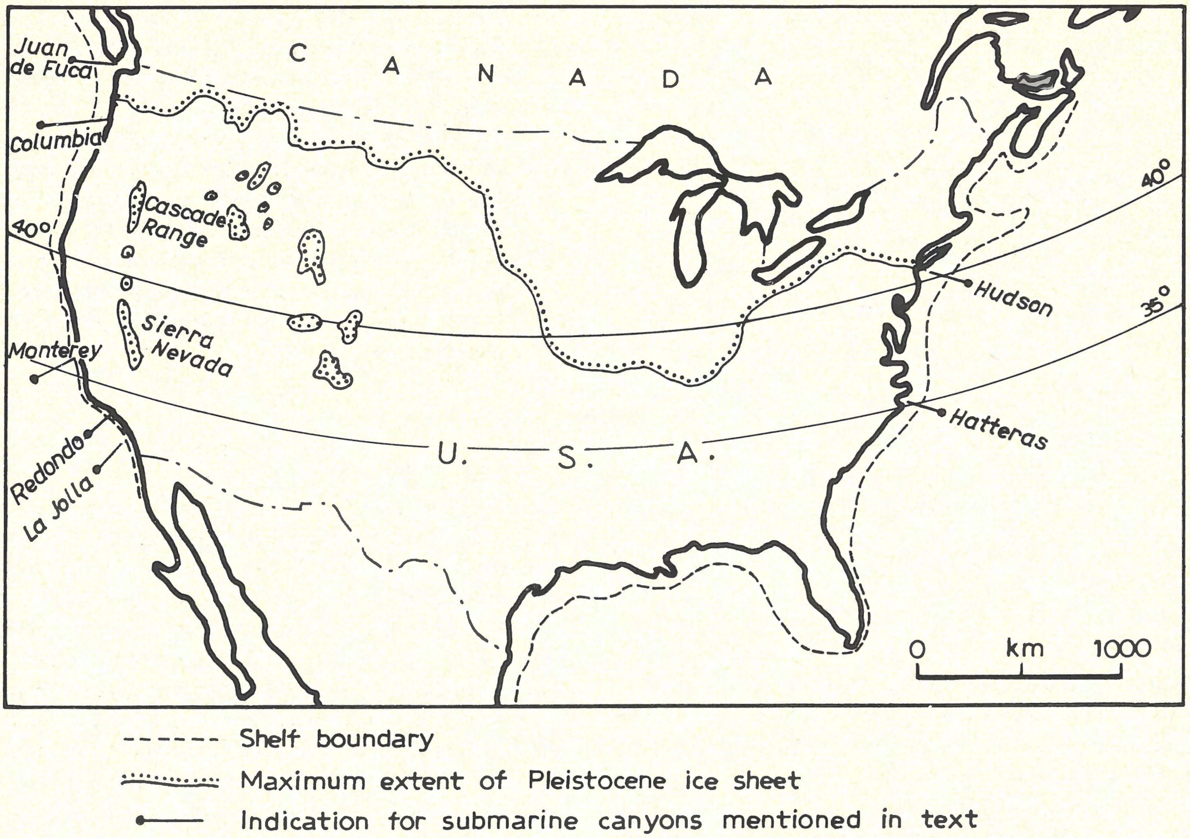
When invading the US river basins, the ice masses brought nearly all waterflow there to a standstill. Along the coast the ice pressed on southward till the 40th parallel (fig. 3).

The general cooling effect of the atmosphere which had initially stimulated the expansion of the ice sheet, ultimately led to a decrease of the temperature of the ocean water. Diminished evaporation caused diminished precipitation: the ice sheet "starved". Ablation which had increased as the ice sheet extended southward, was no longer compensated: deterioration set in, starting along the southernmost border of the ice cap.

As the wasting ice masses bared the continental landscape, enormous amounts of debris were uncovered; draining rivulets carried this detritus downstream.

The rivers had not yet revived, but meltwater floods of enormous magnitude flowed down their riverbeds. G.F. Wright (1911) mentions that J.D. Dana found evidence that during the melting of the ice cover the level of the Connecticut River reached to more than 60 meters above the present high-water mark. The tractive capacity of these gigantic floods must have been unbelievable.

Upon entering the shallow river channel that had been cut through the shelf, the floods overran the channel banks, inundating the adjacent shelf and depositing a deltaic sediment. As the jet of the mainstream, loaded with coarse debris, entered the ocean, sediment first precipitated in lateral embankments, thus extending the stream channel into open water. The ocean rapidly checked the velocity of the



(Based on data of R.F. FLINT and F.P. SHEPARD)

Fig. 3
Schematic map, giving extent of Pleistocene icesheet and width of Continental Shelf. Also indicated submarine canyons mentioned in text.

jet, causing the detritus to settle on the continental slope. As the process was a continuous one, the waterlogged pile on the slope soon collapsed to form a debris avalanche which on its downslope course absorbed more and more water, thereby increasing its fluidity and transforming it into a turbidity flood. Upon reaching the continental rise with its gentle gradient, a fan-shaped submarine fan was deposited.

The debris avalanche, originating at the top of the slope, had high erosional power; canyons were eroded in hard rock, even granite, cutting the V-shaped transverse profiles, characteristic for most submarine canyons.

Upstream erosion of the continental slope moved the canyon head towards the rivermouth, its source of erosion. As a connection was effected the stream of detritus dropped straight into the canyon head. Continued supply of detritus led to continued erosion which locally cut into the shelf over a distance of more than 30 kilometers.

As the ice sheet retreated the meltwater supply gradually diminished and the stream carried less coarse material. No longer the river occupied the entire width of the channel that had been cut into the shelf. Bars and riffles made the stream deviate from its orginal course and scour a new rivermouth.

The debris carrying stream now entered the canyon head from a different direction: promptly the canyon axis veered to point at the new source of erosion. This phenomenon has been labelled the "signpost symptom".

The melting of the ice sheet proceeded and the ocean level rose: the shelf channel was invaded. The sediment carried downstream no longer reached the canyon head, instead it settled on the floor of the estuary.

The US westcoast was never covered by an ice sheet. The Sierra Nevada and the Cascade Range numbered several glaciers and as the drop in atmospheric temperature caused a lowering of the snow line of about a thousand meters, the local glaciers extended, although they never did form a continuous ice sheet (Strahler 1971).

During the glacial age the mountanous West was characterised by a high degree of precipitation and a low evaporation; it numbered around 120 intermontane lakes which were fed exclusively by precipitation. The intensity of the rainfall may be illustrated by the size of the pluvial Lake Bonneville. At

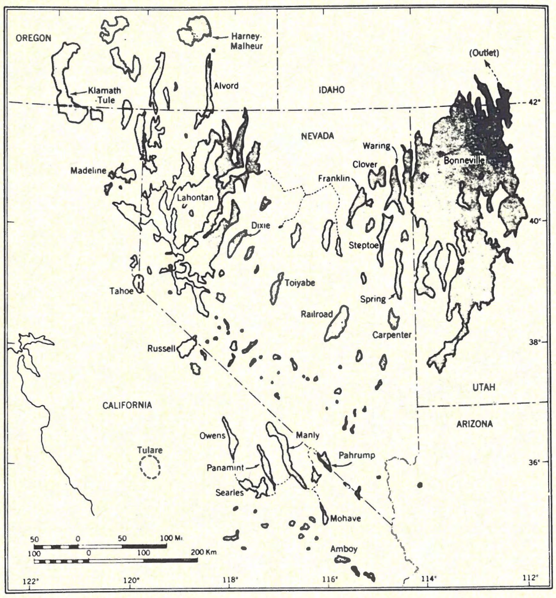


Fig. 4
Pluvial lakes of the western U.S. After R.T. Flint (1957)

its height it covered roughly 52 000 sq. kilometers; its maximum depth was over 300 meters. Its shrunken remnant of today is the Great Salt Lake. (fig. 4)

Prodigious rainfall, combined with considerable relief, characteristic for this part of the US, provided numerous debris laden floods with a high erosional potential. At the foot of the mountains the pluvial floods had only to cross a relatively narrow strip of land to reach the shelf which is much narrower here than along the Eastcoast. The rivers, pouring their load on the continental slope, created streams of detritus which eroded submarine canyons. Upstream erosion quickly cut through the narrow shelf and today many of the Californian canyons head in the vicinity of the beach. It seems unlikely that all canyons after crossing the narrow shelf and reaching the beach, would stop their advance towards their source of erosion. Some of them, cutting through a narrower shelf or through less resistant rock, made faster progress than others. It appears hardly plausible to maintain that no canyons could have crossed the coastline to head inside of it. The only criterion is the presence of a nickpoint, i.e. the sudden increase in slope that characterises the transition from the floor of the landvalley to the slope of the canyon head.

At the end of the pluvial period the pluvial rivers petered out; canyon heads inside the coastline were filled up; outside the coastline longshore drift often partially masks the presence of former depressions. Possibly Redondo Canyon lies at the mouth of a "lost" river. Inside the coastline the canyon shows a broad, channellike continuation, 1.5 kilometers wide and extending 1.6 kilometers inland, "heading" 37 meters below present sea level (Yerkes et al, 1967).

Along the Californian coast many canyons do not show a connection with an existing river. Montery Canyon which in size rivals Colorado Canyon, is one of these. It is difficult to understand how a flood which transported the huge amounts of debris, necessary to excavate Montery Canyon and which subsequently deposited a large submarine fan, could disappear completely, leaving no traces. It only emphasizes that the original riverbed must be exceptionally well masked.

Finally some submarine canyons are neither of glacial nor of pluvial origin. They are not to be found in the US. An excellent example is Congo River with its enormous drainage basin and the largest discharge in Africa, which in addition carries an exceptionally high content of sand.

When during an ice age the ocean level dropped, the continental shelf was gradually bared. Congo River's delta slowly followed the retreating ocean, until finally the stream could pour its load on the continental slope. The upstream erosional process which followed, has been described elsewhere.

At the close of the final glacial epoch the canyon head must have been situated inside the present coastline. The sand supply was dropped on the slope of the canyon head, stimulating upstream erosion; at present the canyon head lies 25 kilometers inside the coastline. During periods of high water descharge the waterlogged pile of sand on the slope of the canyon head collapses, creating a high density turbidity slide, which often causes cable breaks.

This type of canyon has only one thing in common with the glacial and pluvial types mentioned: a flood, carrying a high content of erosive material, drops its load on the continental slope, bared as a consequence of enormous ice caps elsewhere in the world. As in this case the debris transporting fluid is neither of glacial nor pluvial origin, it is suggested to classify Congo Canyon as the drainage type.

A number of canyons and their submarine fans are of mixed origin, e.g. the Ganges-Brahmaputra and several South American river systems. These are not only fed by ordinary tributaries, but in addition by rivers which originate in mountain ranges which during the Pleistocene era were glacially controlled.

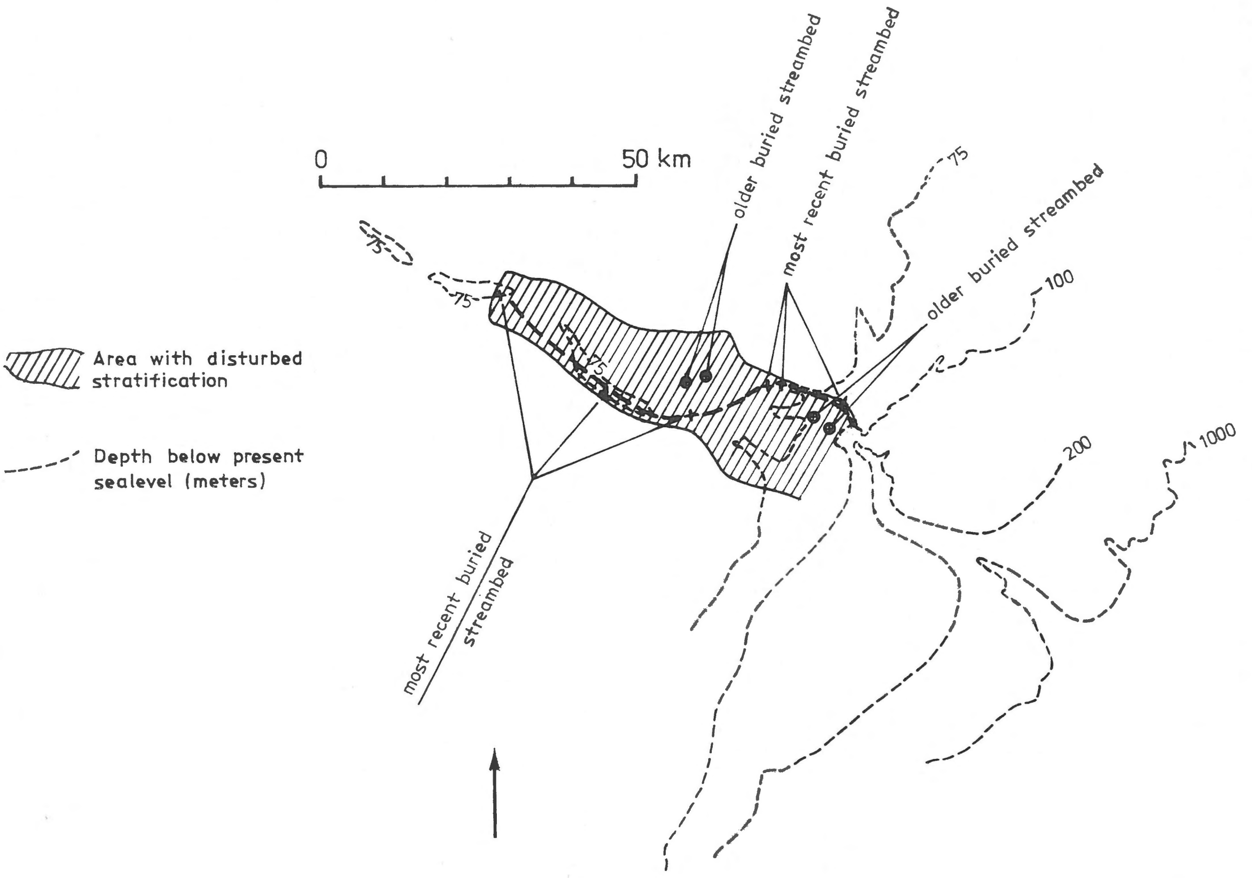
SOME MORPHOLOGICAL ASPECTS

Tributaries to canyons

There are two types of tributaries

a. The "hanging valley" type
b. The canyon type, showing most characteristics of a canyon, including hanging tributaries

It is suggested that the first type originates from streams, lacking the power to cross the continental shelf. Small to moderate amounts of debris were deposited on the shelf. On the eastcoast these streams were fed by glacial meltwater, on the westcoast by pluvial precipitation.



Adapted from Ewing c.s. (1963)

Contours in meters

Hudson channel area

Fig. 5

After a glaciation the rising sea level at high tide inundated a shelf, locally littered with debris; at ebb tide the canyon channel which transversed the shelf, acted as a giant drain, as its waterlevel dropped at a faster rate than the waterlevel on the beach. Rivulets developed, which time turned into permanent drainage channels, entering the canyons as hanging valleys and under a sharp angle, thereby creating the well-known fish-bone pattern. Occasionally upstream corrosion excavated bowl-shaped tributary heads. Shepard and Dill (1966) mention that numerous tributaries of Californian canyons line up with land canyons which show a limited drainage pattern. This type of tributary is canyon-dependent. Along the Californian coast it is quite frequent; along the eastcoast the phenomenon probably went unnoticed amidst the glacio-fluvial deposits of the continental ice sheets.

The second type of tributary is of different origin. During an interglacial period the on-land course of the river which had been supplying the eroding material, was deviated and it now debouched somewhere else along the coast, quite often not far from the original debouchure. A new channel was cut; in case it joined the existing canyon, it did so as a hanging valley, which soon became the main canyon. The upstream part of the original canyon no longer had a function; it was often (erroneously) considered a tributary.

Aprons, canyons and submarine fans

Introduction

By the time the ice sheet that originated in Northern Canada, extended to the US/Canadian border, the level of the oceans had already dropped considerably below the present stand. Hudson River which then still received its normal watersupply, had followed the retreating ocean over the bared shelf to form a new debouchure. Later, when its drainage basin had been overrun by the ice sheet and the river's watersupply terminated, storms and longshore drift filled up the dry riverbed. In the estuary vegetation and marine life, adapted to low temperatures and shallow water, found refuge.

About 15 000 years ago the Wisconsinan glacial period came to an end: deterioration of the ice sheet set in, first along the southernmost border of the ice sheet, which along the eastcoast extended till the 40th parallel.

According to Milliman and Ewing (1968) the melting process proceeded at a fast pace. The influx of the first meltwater from the North American ice sheet swept the Hudson Channel and its estuary clean of the accumulated clay, sand, debris and organic material, dumping it over the shelf/slope rim into the ocean and onto the slope; ultimately it was deposited at the canyon gorge, building a pell-mell deposit of clayballs, silt, sand and shells of shallow orgin. It is suggested that this deposit is identical with Ericson's "pebbly mud" (1952). It also provides an explanation for the side-by side presence of shallow and deep-water foraminifera in a core from Hudson Submarine Fan (Richard and Ruhle, 1955).

Origin and morphology of Hudson Apron

After the preliminary melting of the ice sheet, giant turbidity floods swept down the Hudson Shelf Channel, spilling over its banks and inundating an extensive area. The Apron must have grown at an amazing pace, as the rapidly deteriorating ice sheet supplied enormous amounts of meltwater, heavily laden with detritus. In addition the firm, flat, horizontal shelf stimulated fast growth.

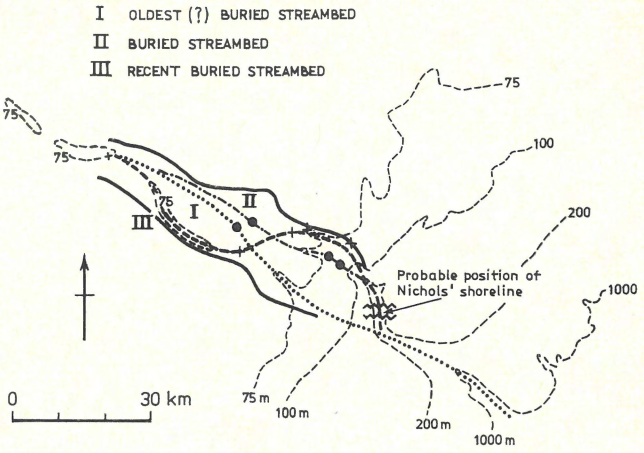
It should be emphasized that most of the suspended material carried by the overspilling floods, consisted of clay, silt and fine sand. The coarse material was primarily transported as bedload. The sediments of Hudson Apron will therefore mainly consist of clays and silts, only occasionally intercalated with fine or medium-grained sand.

The concept submitted is in agreement with Ewing's point of view that Hudson Apron is a delta, built in a period that most of the shelf was subaerial.

The *Hudson Shelf Channel* (fig. 5) consists of disturbed sediments deposited in a broad valley by successive meandering streams. The most recent buried channel was traced to the head of the canyon. An older channel approximately followed the same general course, although about 13 meters deeper. Some still deeper channels, indicated at about – 155 meters, may well be correlated with a stand of sea level which produced a buried shore with wave-cut terrace. This shore was first detected by Veatch and Smith (1939) and named Nichols' shore. Nearby a core was drilled; a C^{14}-date of an assemblage of broken shells in this core indicates an age greater than 35 000 years.

Several well identified channels were registered near the present canyon head at depths of respectively 97, 122 and 156 meters. One profile across the present canyon head showed the presence of a channel, considerably deeper (202 – 260 meters).

Below the 200 meter-contour the axis of Hudson Canyon is practically in line with the axis of the Hudson Shelf Channel. In addition the 75 meter-contour near the right bank of the channel shows a long, narrow indentation, doubtlessly resulting from local erosion, and exactly fitting in the concept that the oldest streambed followed the course, indicated in fig. 6 (1).



HUDSON CHANNEL AREA

RECONSTRUCTION OF FORMER STREAMBEDS
(From data by EWING cs 1963)

Fig. 6

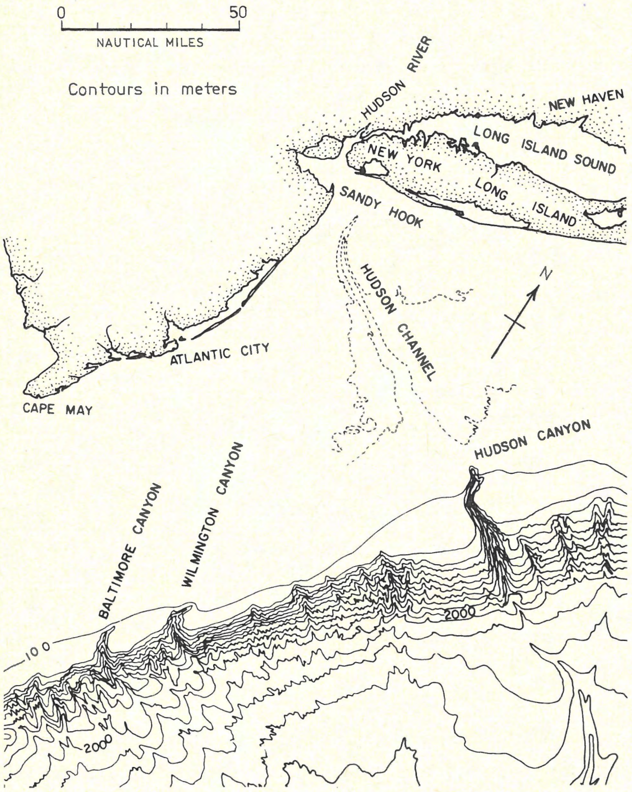
The sudden swerve of the upper part of Hudson Canyon and its head is in accordance with the "signpost symptom": the cause of the sudden change of direction has to be attributed to a change in the position of the debouchure of the eroding stream. The local configuration of the 100- and 75-meter contours in combination with Ewing's reflection data confirm this conclusion.

The most recent streambed lies still further northeast where it hugs the left bank. In accordance with the "signpost symptom" the canyon head followed suit (see fig. 5).

The Wilmington and Baltimore Canyons

Southwest of the Hudson Channel the Wilmington and Baltimore Canyons show a pecular aspect. When looking upstream the axes of both canyons run approximately perpendicular to the shelf/slope rim. Upon reaching the shelf both axes bend sharply to the right, pointing in the direction of the Hudson Channel. According to the "signpost symptom" the Hudson Channel should be the source of erosion. It is suggested that the Hudson Apron was a delta of the birdfoot type and that distributaries extended from the Hudson Channel to the respective heads of Wilmington and Baltimore Canyons (fig. 7).

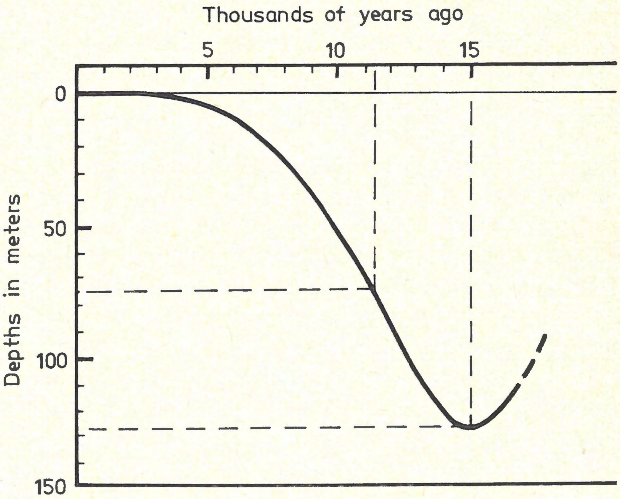
On its course down the slope the Hudson Canyon does not show extraordinary characteristics: it only served to guide the eroding debris avalanches and turbidity floods to the continental rise.



SITUATION OF HUDSON, WILMINGTON AND BALTIMORE CANYONS

From a map by Elazar Uchupi

Fig. 7



Sea-level curve for the past 15.000 years
(After J.D. Milliman and K.O. Emery)

Fig. 8

The Hudson submarine fan

When the debris carrying floods emerged from the canyon mouth and penetrated the standing body of water at the foot of the slope, their velocity was rapidly checked. Lateral embankments were built and overflowing and spreading deposited the upper fan. Turbidity floods carrying gravel, sand, silt and mud proceeded down the continental rise with its very low gradient, leaving lenticular deposits in the submarine channels and building natural levees up to 30 kilometers wide and rising more than 250 meters above the adjacent abyssal plain (Nelson and Kulm, 1973).

Owing to a multitude of causes, e.g. landslides, collapsing ice barriers, local blocking of canyons, etc. the intensity of the turbidity floods rushing downslope, fluctuated considerably. The upper fan deposits, often submitted to intensive churning and pounding, were repeatedly destroyed and rebuilt. Consequently they show a complete lack of sedimentary structure.

As periodically new powerful floods broke over the fan, lenticular sediments were swept away, levees overrun and broken through as new distributaries were cut. Often the outer curve of meanders was undercut and collapsing levees carried downstream. The submarine fan deposits therefore will show no continuity and coarse material will often be found far out on the abyssal plain.

Nevertheless some marine fan deposits have brought to light indications for the existence of several episodes of turbidite deposition. Both Curray and Moore (1971) and Huang and Goodall (1970) suggest that some of the largest fan systems apparently have an extensive history encompassing several episodes of turbidite deposition. Kulm, Von Huene et al (1973) found near Juan de Fuca abyssal turbidites under Astoria Fan deposits, thereby providing support for the hypothesis submitted.

The duration of the canyon excavation process

The continuous melting of the ice sheet resulted in a rise of the ocean level. According to an approximation, based on the work of Milliman and Emery (1968), the period of canyon excavation did not exceed 3 500 years (fig. 8). About 11 000 years ago the rising sea level must have reached the 75 meter contour and it thereby put an end to the deposition of debris in the canyon head.

Wherever canyon heads had moved upstream till they had reached the coastline or even moved inside of it, the rising sea level had little effect on the supply of the eroding material provided. As long as the rivers carried enough debris to the canyon head, the eroding process went on.

Observations on some other canyons

The Magdalena River is of the drainage type. Its lower reaches, about 800 kilometers long, are characterised by swamps, lagoons and lakes, forming an area favourable to deviations of the river course. The submarine contours off Magdalena Delta (fig. 9^a) show several submarine valleys; only part of these have a connection with the present river course. They suggest the existence of two valley systems, separated by a ridge. The eastern system shows some rather poorly developed submarine valleys, two of which barely indent the 50-fathom contour. It is surmised that the main stream in a former period of low sea level debouched in the eastern lagoon, subsequently eroding two or possibly three valleys.

The morphology of the western lagoons around the pre sent river mouth, the curved sandspit west of it, and the submarine contours of the most western canyon, suggest that the main stream of Magdalena River once had a westerly direction. Before settling on its present course it subsequently fed the western and northwestern valleys which both have canyon heads inside the 50-fathom contour. The latter valley heads close to the western bar of the present river extension into open water. In 1935 this western bar collapsed.

The flood, pouring through the break, caused the existing accumulation of debris on the slope of the northwestern canyon head to collapse: 480 meters of the breakwater disappeared and a channel, 11 meters deep, was produced across the bar. The debris slide resulted in a cable break in the north-western submarine valley, 25 kilometers offshore (fig. 9^b).

The *Corsican canyons* are generally cited as an example of drowned canyons.

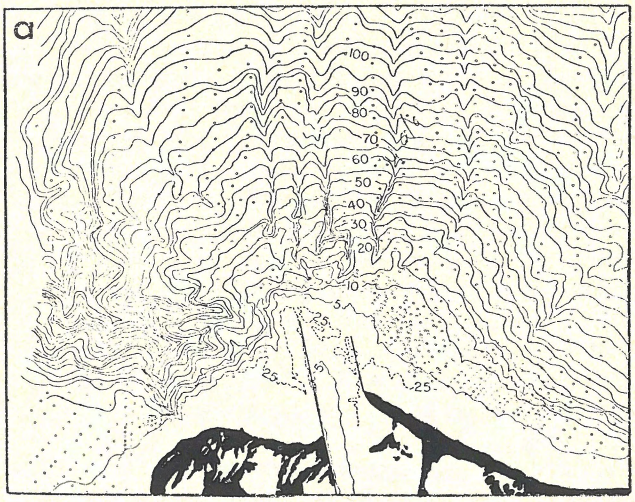
Even Kuenen (1953) who strongly supported the turbidity current hypothesis, proved convinced that these canyons had been drowned. The submarine fans that most of the West-Corsican canyons show, are however not in agreement with this point of view.

On the basis of the hypothesis sketched above, another explanation is submitted. When a large part of Europe was covered with an ice sheet, northern Africa experienced a pluvial climate (Holmes 1965). Although few details are available about the extent of the mediterranean pluvial belt, it seems plausible to assume that Corsica formed part of it. The mountanous area along the western coast immediately suggests a parallel with the US westcoast.

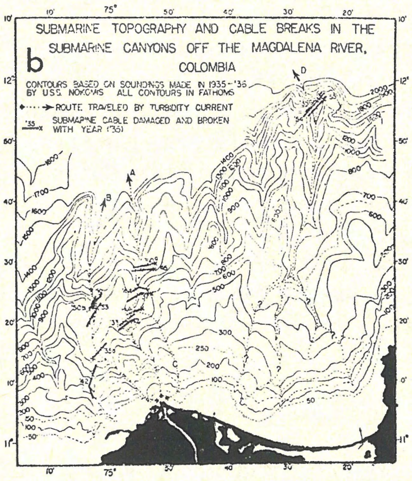
In Corsica also a pluvial period would produce mountain streams with a high erosional potential and canyons would rapidly erode their way through the shelf and proceed up the streambeds of the connected rivers. The canyon heads later were masked effectively. In their introduction to an article on Congo River Shepard and Emery (1973) remark that "a group of canyons along the Westcoast of Corsica heads into relatively deep estuaries of small rivers."

A previously reported absence of nickpoints is readily explained, as the search for them probably did not extend to the riverbeds.

The submarine contours show some submarine canyons off the northwestern coast which apparently do not have a connection with an existing river. It is suggested that these canyons which head offshore, were fed by a "lost river".



Detail of gullies off Magdalena Delta (From HEEZEN 1956)



Figs 9^a and 9^b

From Elmendorf and Heezen (1957)

Fig. 9^a and 9^b

CONCLUSION

The phenomena observed led the author to infer that the lowering of the ocean level below the shelf/slope rim is a prerequisite for canyon excavation.

Actual excavation took place as a powerful stream, transporting large quantities of coarse debris, poured its load on the continental slope. The resulting waterlogged debris pile collapsed under continuous overloading and rushed downslope, eroding a canyon.

It is quite probable that during Pleistocene several glacial periods of less severity occurred. As in these cases the sea level did not drop below the shelf/slope rim, no canyons were excavated. Certainly deltas and deltaic structures were built which in time were destroyed by minor transgressions.

There is evidence that canyon excavation is still taking place today, although as a periodical process. The debris supply will be less and it will primarily be deposited on the increase in slope, provided by the canyon head. During periods of high water discharge and a high rate of sand supply, a situation of overloading is created, resulting in a sand slide (avalanche) eroding the canyon. The frequent cable breaks along the Congo and Magdalena Coasts first focussed attention at the special circumstances resulting in cable breaks.

It seems that a canyon head with a depth of 21 meters is capable of initiating sand slides which continue flowing as the gradient of the river bottom has decreased to 10 meters per kilometer, i.e. a gradient of one percent.

Finally a few remarks concerning the oil possibilities in submarine fans.

It should be emphasized that submarine fans are, geologically speaking, of recent origin. When they are oil-bearing the oil most likely would be a product of secundary migration: it was originally accumulated elsewhere and a second migration took place after a fault had opened the original reservoir. Oil bearing submarine fans are therefore principally to be expected in tectonically active areas.

In addition submarine fans are situated at the base of the continental slope, at depths which at the moment place many of them outside the reach of to-day's oil technology.

VERIFYING THE VALIDITY OF THE CONCEPT

1. If canyon excavation indeed proceeded along the lines of the hypothesis the process was repeated several times. Along the glacially controlled coasts several times giant meltwater floods poured coarse detritus on the slope, from where it proceeded towards the submarine fan. Long cores, drilled on the fringes of the Hudson Fan would uncover proof of several sedimentation cycli.
2. Additional investigation would prove the existence of "lost" rivers of pluvial origin.
3. If the ideas about the puzzling deviation of Wilmington and Baltimore Canyons be correct, continuous reflection profiling would detect buried channels, connecting both the canyon heads mentioned with the Hudson Channel region.

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