THE UNDERLYING CAUSES OF SUBMARINE CANYONS

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As more and more deep submarine canyons are discovered off the various coasts of the world it is quite natural that much skepticism should be aroused relative to their origin as stream-cut valleys. Alternative modes of origin not involving large scale movements of the continental borders have been suggested recently by two of the foremost American geologists. The late Professor W. M. Davis\(^1\) called attention to the possibility that winds sweeping water into a bay might set up a return current underneath which would keep open a valley-like depression while sediments were accumulating on either side. Professor Daly\(^2\) on the other hand suggested that during the low sea level stages of the glacial period the waves might have attacked the mud banks of the outer continental shelves and that the resulting heavy muddy water would have moved down the continental slopes excavating submarine canyons where the flow became concentrated.

During recent years the writer has been given splendid coöperation from many organizations\(^3\) in the exploration of these marine canyons and during this work has made every attempt to check the possibility of origins other than fluviatile. The large accumulation of data which has been acquired appears to have much bearing on the subject. To summarize this information: In the first place the canyons which have been surveyed in great detail are proving to have a close resemblance to river canyons on land. For example, it is perfectly obvious that a canyon with tributaries like the one shown in figure 1, which is from a model of the Monterey Bay submarine canyon, is the type of feature which rivers cut on land,

\(\ast\) Paper No. 30, published under the auspices of the Committee on Geophysical Research at Harvard University.


\(4\) L. D. Leet and W. M. Ewing, Physics, 2, 160 (1932); L. D. Leet, Physics, 4, 375 (1933).

\(5\) R. L. Wegel and H. Walther, Physics, 6, 141 (1935).

\(6\) E. Giebe and E. Blechschmidt, Ann. Physik, 18, 417 and also 457 (1933).


\(8\) R. Ruedy, Can. Jour. Research, 5, 149 (1931); also Ibid., 13, 10 (1935).
but quite different from the small channels and depressions which are
definitely known to be due to submarine current scour. Also, the huge
branching canyons with their axes shown in figure 2 are certainly of a
fluviatile pattern.

In the second place the suggestions of possible current origin seem to
have been made with the idea that the canyons penetrated soft sediments,
but the exploration by the writer of 14 canyons on the west coast has
shown that 11 have rocky walls, some with hard rock, even solid granite.
In the investigations of H. C. Stetson off the east coast rock was also found
in two canyons. It seems impossible that the narrow canyons with rocky

![Figure 1](image_url)

**FIGURE 1**
Model of Monterey Submarine Canyon constructed by Blackstone Model Company.

walls found off California could have been formed by ocean currents.
Also, it is beyond all reason to suggest that a canyon like the one in figure
3 which compares so well with the Grand Canyon could be cut by the
feeble submarine currents which are all that the dynamic oceanographers
consider possible out in the open ocean. Furthermore, both direct mea-
surement of currents and study of water samples from the canyons give a
decided negative to the current hypothesis so far as present information
goes. Finally, the penetration of numerous canyons right up to the coast
does not allow the application of Daly's hypothesis in many cases, nor
does the coastal configuration permit the use of Davis' idea in most cases.
Despite these objections we should make further investigations of currents,
particularly to see if they have not been a factor in keeping open canyons
which were originally cut by rivers.
Since it seems evident that the canyons are not the product of current action and since it is obvious that they have shapes quite unlike those of diastrophic depressions, there appears to be no alternative but to believe that at least the American canyons were cut by rivers. To what extent

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**FIGURE 2**

The trends of the canyons along the California coast from Lucia to Santa Cruz. Depths given in feet.

the same origin can be applied to the hundreds of canyons found around the various other coasts of the world can be decided only after more soundings have been made, but in the mean time the available evidence favors subaerial erosion for the marine canyons of the world.

From this conclusion we must infer that all or practically all of the continental borders stood higher in relation to the sea during some part of the
geological past in order to allow rivers to entrench themselves into these margins. This might mean that the margins were uplifted some time during the past, the canyons cut, and then the margins depressed. However, this sequence is hard to defend for the following reasons: First, such uplifts and subsidences could scarcely be expected to be as universal as would have been necessary. Second, the canyons are as well developed off what appear to be stable coasts as off the mobile coasts such as California. Third, the canyons appear both off coasts which have been sub-

![Figure 3](image-url)

**FIGURE 3**
Section of Monterey Submarine Canyon compared to the Grand Canyon. Note that the same scale and the same spacing of observation points is used.

siding for long periods receiving large thicknesses of sediment and off coasts where uplift is indicated by wave-cut terraces. Fourth, the rocks dredged from the walls of some of the canyons contain fossils or stratigraphic indications of being late Tertiary or Pleistocene in age, but there is no evidence of sediments carried inland from any recently elevated margins.

Another hypothesis which would at least account for the universality of the submarine canyons is that the ocean basins sank drawing the water off the lands and then presently returned to their former position drowning
the canyons. This idea also has serious drawbacks. In the first place, the oceanic islands, particularly the coral islands, have abundant evidence of having been involved in the general withdrawal of the ocean waters. Secondly, it would seem to be mechanically impossible for the ocean basins to undergo such sinking. There is no place for the rock beneath the basins to go, and shrinkage of volume enough to account for thousands of feet of sinking is inconceivable. Thirdly, the reversal of the movement offers still more formidable difficulties.

![Figure 4](image)

**FIGURE 4**

A map showing the direction of the ice movement in Northern Russia and Siberia based on a recent Soviet publication.

Another hypothesis which at least is not open to the various objections of the previous suggestions is that the level was changed due to formation of enormous ice caps on the land which would allow the cutting of valleys on the sea floor to the extent that the sea level had been lowered. The effects of such a change would be as great on the islands of the ocean basins as on the continental borders. Also, there is a mechanism here to account for the lowering of sea level to produce the canyon cutting, and for the canyon submergence. Furthermore, the time of lowering fits in with the
Map showing the possible distribution of ice caps during the maximum glaciation of some early epoch.
available evidence as to the time of excavation at least of the inner canyons, namely, during the middle or early part of the glacial period.

The first problem raised by the glacial lowering of sea level is whether the ice could have been large enough in volume to account for it. There is no use in trying to claim that most of the ocean was piled on the lands lowering the sea level over ten thousand feet and leaving only a greatly shrunken and very salty ocean. On the other hand let us see if we cannot obtain some help from a less radical lowering. Common estimates of the reduction of sea level during the glacial period are of the order of 300 feet. These estimates, however, have been made with extreme conservatism. An average thickness of all the ice caps of only 3500 feet has been allowed, but we know that near the margin of the American ice cap there was over 6000 feet of ice to cover Mt. Washington, and also that the ice in central Greenland is even now about 7000 feet thick. The estimates of the area covered by the ice caps may also be much too small, particularly in regard to the earlier glacial epochs. New evidence suggests that the Arctic ocean may have supported an ice cap starting as shelf ice and gradually sealing in the Arctic basin and building a dome on top of it. The thickening of the shelf ice would have caused it to ground on the relatively shallow margins of the Arctic basin, particularly as the seal level became lowered by growth of ice elsewhere. Figure 4 is based on a recent Soviet publication and is one of several lines of evidence favoring the Arctic ice cap. At the same time the Antarctic ice cap may have grown and extending seaward as shelf ice it could have spread across Drake Strait forming a continuous cap as far north as South America. Possibly it may have extended to other continents although the deep intervening oceans would have greatly interfered. If the ice covered the area shown in figure 5 and had a thickness of 4 miles which is physically and meteorologically reasonable the sea level would have been lowered some 3000 feet. A still greater area and thickness of ice is possible, but even the 3000 foot estimate would account for the universality of canyons and for the indications of submergence of the oceanic islands. It does not, however, account for the deeper parts of the canyons.

The following suggestions are the best that the writer can offer at present as a general explanation: First, that prior to the glacial period there were various depressions on the continental slopes which were in part the result of landslides or mudflows, in part diastrophic, and in part true river canyons submerged by diastrophism. Second, that the sea level was lowered 3000 feet or more during the maximum glaciation of some early epoch and that the rivers from the land flowed into the various preexisting depressions and cut true river canyons through relatively recent sediments connecting these canyons with the deep outer depressions. Third, that the sea level rose with the melting of the ice and that the canyons have been
maintained ever since on the steep slopes due to the mud flows which are still occurring from time to time and that currents may have played some part in keeping the canyon heads clear of sediment.

3 Grants for this work have been made by The Geological Society of America and the National Research Council. Also, much assistance has been given by the Coast and Geodetic Survey, The Scripps Institution, The Hopkins Marine Station and many other organizations and individuals.
4 R. A. Daly, Changing World of the Ice Age, p. 46 (1934).

ON THE MECHANISM OF INHIBITION OF CRAYFISH MUSCLE

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Recent work in this laboratory has demonstrated the distribution and the function of the various motor and inhibitory axons innervating the muscles of the cheliped of Cambarus clarkii. For instance, it was found that the adductor of the dactylopodite is innervated by two motor fibres, giving rise respectively to a twitch and to a slow contraction; that one motor fibre innervates both the abductor of the dactylopodite and the extensor of the propodite, but that each of these muscles has its own inhibitory fibre; and that the flexor of the propodite is triply innervated, having a fibre giving rise to a "fast" and one to a "slow" contraction and a third one stimulation of which can inhibit both these contractions. These facts have been used to carry out experiments on the mechanism of inhibition. This paper is a preliminary note on this work.

Method.—The method of preparing the nerve fibres involved has been described in detail in the two above-mentioned papers. For stimulation, induction shocks were used (faradic or break shocks of variable frequency up to about 80 per second). The contractions were recorded isotonically on smoked paper or isometrically on photographic paper. In the latter case the action currents were recorded on the same paper, using a Matthews oscillograph.

Results.—We investigated the effect of stimulating the inhibitory fibre with different frequencies, the motor fibre being stimulated at a constant frequency of about 50 per second. The frequencies at which inhibition was just noticeable (minimum) and those at which it was complete (maximum) were determined. This experiment was performed on the abductor, on the