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Central subsidence. A new theory of atoll formation

by

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Introduction

The Xarifa-Expedition to the Maldives and Nicobars in 1957/58 was an undertaking of the International Institute for Submarine Research at Vaduz, Liechtenstein, a private foundation of mine. It was partially sponsored by the Max Planck Gesellschaft at Goettingen and the Ministry of Culture of North Rhine-Westfalia. I had hoped that the main part of the costs would be contributed by the Deutsche Forschungsgemeinschaft; unfortunately this was not possible and I therefore covered the costs by producing 26 television programs for the BBC and German television. It had been my intention to investigate the development of atoll formation, as I hoped that underwater investigations in the Maldives might perhaps throw light on this still obscure problem. In the circumstances, however, my time was almost entirely absorbed by film work and the management of the expedition. For this reason the following arguments can only be substantiated in a very general way. As I see no opportunity to carry on this research in the near future, and as my theory may perhaps give others a lead, I decided to publish the following short account from my book "Expedition ins Unbekannte" published by Ullstein, 1961. This book will eventually be translated into English and published by Hutchinson, London; it also includes a list of the scientific papers giving the results of this expedition.

Atoll formation

Darwin considered that some of the islands surrounded by coral reefs had subsided in the course of time until finally they had disappeared completely beneath the surface of the sea, and that at the same time the original fringing reef had grown higher and higher until it finally remained as a ring in the sea.

On the other hand, Murray and others have explained the formation of atolls by a rise in the ocean bed. In this way a rise of the bed to within perhaps 50 meters of the surface would be followed by the onset of

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[1] Ergebnisse der Xarifa-Expedition 1957/58.
[2] Internationales Institute für Submarine Forschung.

Note. We are publishing this paper in spite of the negative reactions of some of our advisors, not because it represents in any way the conclusions of the Pacific Science Board Coral Atoll Program, or of the editors, but because it is the editorial policy of the Atoll Research Bulletin not to suppress ideas that arise from field observation. It must be pointed out that the observations suggest that the structure of Maldivian atolls must be very different from that of the Central Pacific Atolls with which we are familiar.--Eds.

growth in reef-building corals. As conditions would be more favorable on the outer edge, there would be greater growth there, and so a ring would be formed.

A third theory (Daly) is based on the fall of the sea level during the last Ice Age and the subsequent cooling of the water. This would have caused the death of the corals followed by wave erosion of the reefs, leaving large, bare platforms. When the sea rose again and the water grew warmer, new coral growth would have begun, principally on the outer edges, and so the familiar ring would have been formed.

An aerial survey of the reefs in the Maldives has suggested to me quite a different theory. All stages of development can be seen here. Firstly, isolated cone-like growths appeared and just reached the surface. There were also larger growths in which the centers had sanded over, though coral still appeard to be growing strongly on the outer edges. Finally, there were the typical reef rings surrounding beautiful blue lagoons (figs. 1-5). The depth of the lagoons seemed to bear a direct relationship to the size of the atoll: the larger the reef, the deeper the blue of the lagoon. It occurred to me that the rising and extending reefs first became barren in the middle and then subsided in the center like a piece of cake. The farther they extended outwards the more they sank in the middle.

Subsequent underwater investigations showed that this first impression of an uninterrupted transition from a small coral reef to an atoll was not mistaken, and led me to an observation which threw new light on the old problem. I discovered, in fact, that the inner structure of these reefs is by no means as firm and solid as has been assumed. They are actually built by very delicate, much branched corals, such as Acropora and Echinopora which grow up over each other to form a kind of loose scaffolding (figs. 6, 7). When the coral dies, fragments break off and roll down to form a slope of loose debris extending into deep water at an angle of about 45° (fig. 8).

At a depth of about 18 meters, I tried to drive a tunnel into the side of the reef, and found this quite easy to do, even with my bare hands. The structure was, however, so loose and shifting that it soon became undermined and collapsed.

These facts suggest a simple explanation to account for the formation of atolls. As the reef rises and extends outwards on all sides by growth and the accumulation of debris, the lattice work of corals which was at first on the outside becomes part of the inside of the reef and thus subject to the weight of the debris lying above. In the course of time, the calcareous material becomes brittle, possibly even re-crystallizes, and thus causes the originally loose structure to collapse under the pressure from above. This process obviously bears some relationship to the age of the reef itself, as one can see very clearly in the Maldives. With a ring diameter of about 2 km, the depth of the lagoon is between 10 and 20 meters; a diameter of 8 km gives a depth of up to 40 m, a diameter of 24 km a depth of 70 m, and so on.

As other observers have mentioned, the lagoon itself does not fill up again with corals because the environmental conditions there are unfavorable for their growth. We were able to follow this general process very closely in the Maldives (figs. 2-4). As soon as a reef reaches the surface and begins to spread out in all directions, a barren area forms in the middle, something like a bald head. Here there is a double relationship between cause and effect. The more favourably placed corals flourishing on the outer edge take a greater share of the available oxygen and food, with the result that the corals growing in the middle gradually perish and crumble, forming coral sand. This sand is then swept backwards and forwards by the tides and so helps to smother the surviving corals. In this way a reef with a diameter of perhaps not more than 300 m will become a miniature atoll with a center growing progressively barer and at the same time starting to subside.

The rate of subsidence is probably influenced by the particular solidity of the upper part of the reef, the so-called reef flat. This firmness is due chiefly to calcareous algae which live only in shallow water. They cover all the coral fragments with a crust and join them firmly together so that--as the reef extends--a solid platform develops resting on the porous mass below (fig. 10, A, B). Only when this platform has reached a certain size and has become barren and sandy in the center does subsidence set in (fig. 10, C, D). This suggests that possibly the center of the platform, when it becomes barren and covered with sand, somehow disintegrates and loses some of its firmness.

Another point may also play a part here: the larger the atoll, the greater the volume of water enclosed in relation to the circumference of the reef. It must be remembered that whereas the circular reef merely extends in one dimension by an increase in circumference, the enclosed water increases by the square. More outlets thus become necessary to allow the tidal water to flow in and out of the atoll. At ebb tide the water is trapped inside the atoll, and until it finally manages to flow out its level is a little higher than that of the surrounding sea (fig. 11). This means that for some time there is a greater pressure on the bed of the lagoon, and it is quite possible that in the course of thousands of years this constantly changing tidal pressure may influence the subsidence of the lagoon bed, by a kind of rhythmic massage.

It may seem that this idea is incompatible with the porous structure of the reef as described above, but here again the firmness of the reef flat must be considered. The reef flat represents a more or less impervious bottom resting--after subsidence--like a cup on top of the porous structure. From time to time sudden tropical rainstorms may also increase the volume and weight of the trapped water. In this way a downward pressure is exerted.

Only as the atoll grows and channels appear in the ring will the conditions for coral growth in the lagoon again improve progressively. Secondary fringing reefs will then form along the inner margin of the atoll, causing a considerably steeper slope (fig. 12, F), and secondary cone-like reefs will grow up from the lagoon bed (fig. 12, R). This completes the chain of development which is typical of the Maldives. The

secondary lagoon reefs experience, of course, the same extension and subsequent central subsidence, and this explains the presence of small rings within the larger ones (figs. 9 and 12 A).

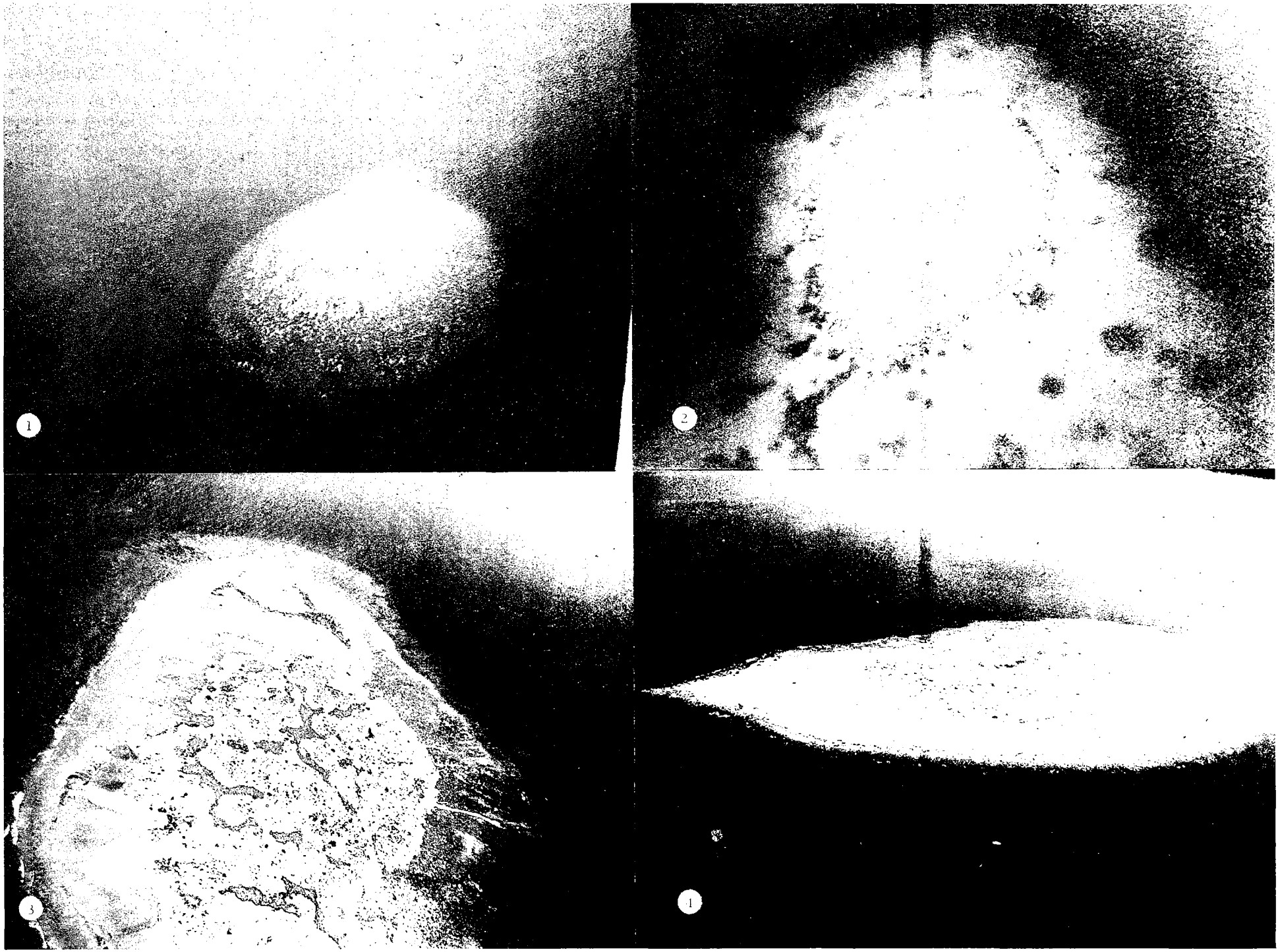
The theory put forward here also accounts for the formation of barrier reefs. If a fringing reef continues to extend towards the sea, then, by the same reasoning, the rear section gradually subsides and a deepening lagoon is formed between the land and the reef. The theories of upheaval and abrasion do not sufficiently explain the fact that the larger the atolls are, the deeper they become, and also the lagoons of barrier reefs become deeper as the reef extends farther out from the land. The present theory, on the other hand, gives an explanation of both these phenomena.

Few theories have accounted for the fact that atolls exist only in certain tropical areas. My answer to this problem is simply that the reefs are not everywhere built by the same kinds of coral.

The particular firmness and solidity of the upper part of the reef has, in my view, led to a misunderstanding. Scientists who have not had the opportunity to dive have been misled by this solidity of the reef flat to assume that its inner structure was similarly firm. In the Red Sea, where the more compact Porites corals play a greater part in the building of the reefs, this may well be so, but this is not so in the case of the Maldive reefs. Here too the platform spreads out like a solid mass of concrete, but the foundation on which it rests is loose and porous. The fact that it takes a long time before this platform actually subsides in the middle may be due to static factors and to a natural disintegration of the material in the center.

Whether this theory of central subsidence satisfactorily accounts for every known ring formation is another matter. As Hoffmeister and Ladd have pointed out, it is possible that not all atolls have been formed in the same way. Some may have come about through the rise or fall of the ocean bed, and others through ice age abrasion. However, amongst the various possibilities I feel that the present theory is entitled to some consideration, particularly as it has in fact the advantage that it does not rely on either a rise or a subsidence in the ocean bed or on a fall in the sea level, but explains the origin of both atolls and barrier reefs from the normal processes of coral growth.

Summary: Reefs built mainly by slender branching corals have a porous and unstable inner structure. This causes the more extensive reef flats to subside in the center. Such central subsidence may possibly be further influenced by re-crystallization of the underlying material, by the disintegration of the material of the center of the reef flat itself, and by the cumulative effect of changes in water pressure in the lagoon caused by the tides and occasional rainstorms.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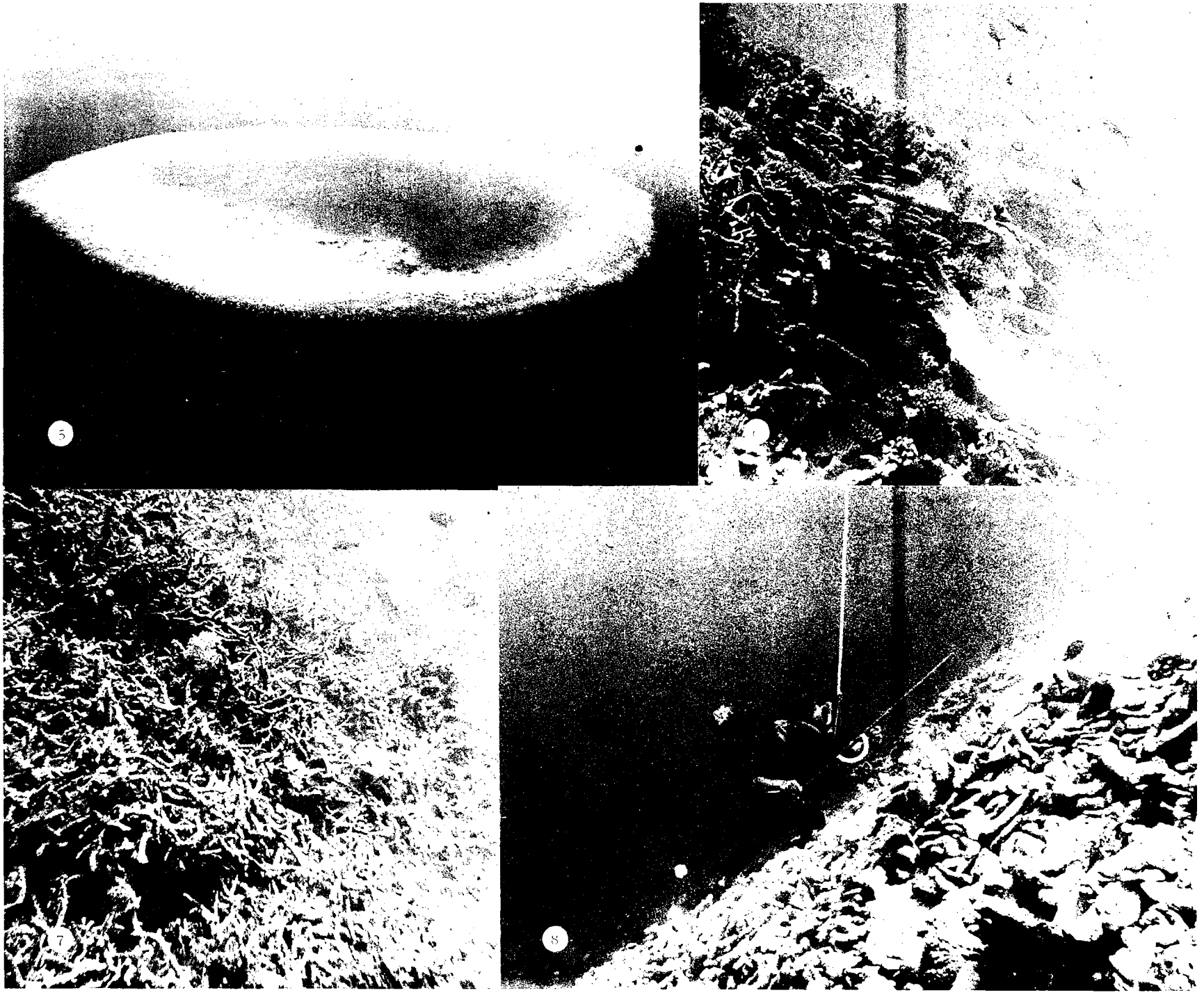
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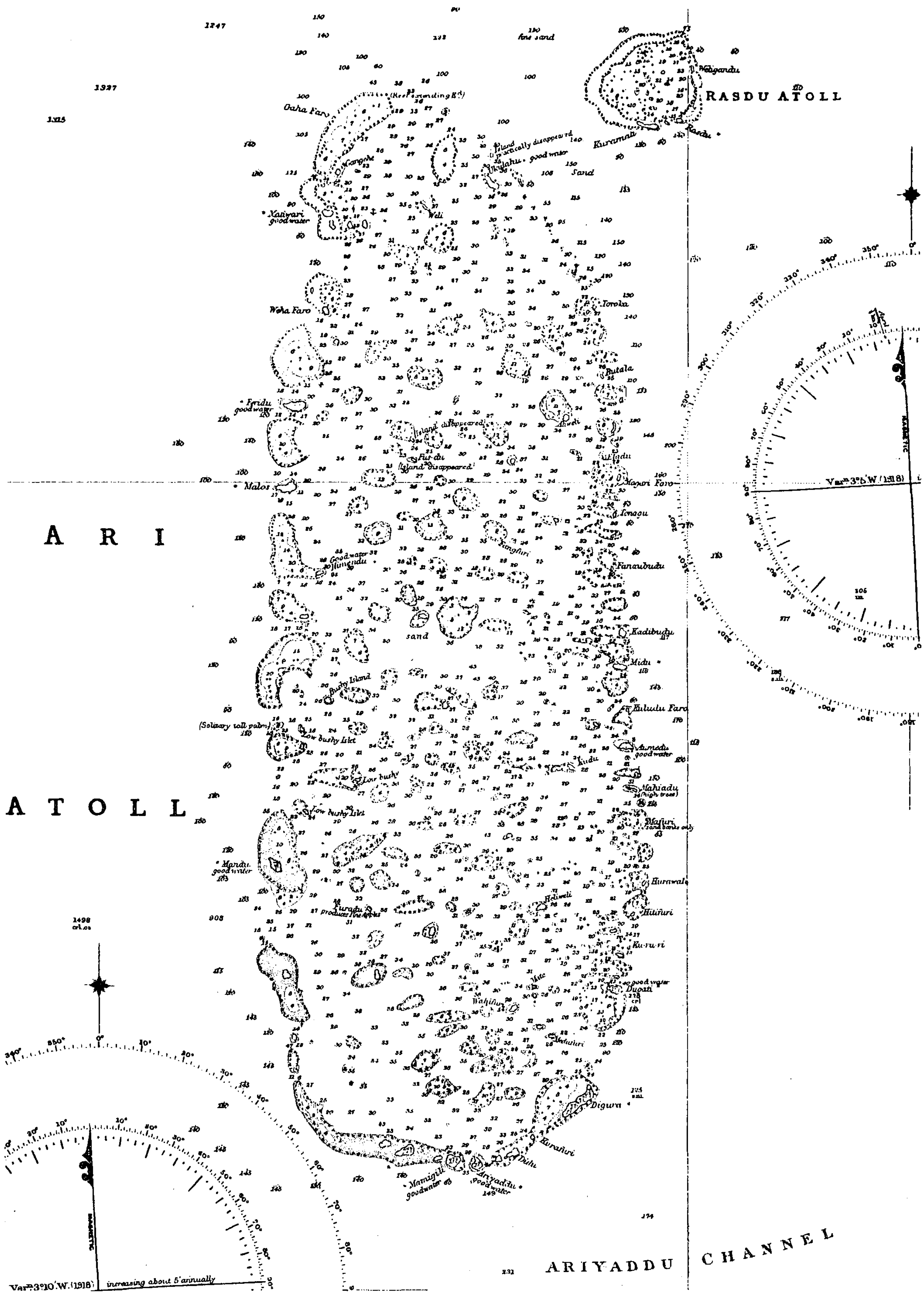
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Midu
sand
Bushy Island
Low bushy Islet
Mahiadu
Huruwali
Hitifuri
Kururi
Digura
Mamigili
Ariyaddu
ARIYADDU
CHANNEL
Varn 3°10'W.(1918) increasing about 5' annually
Varn 3°5'W.(1918)

Figure 9

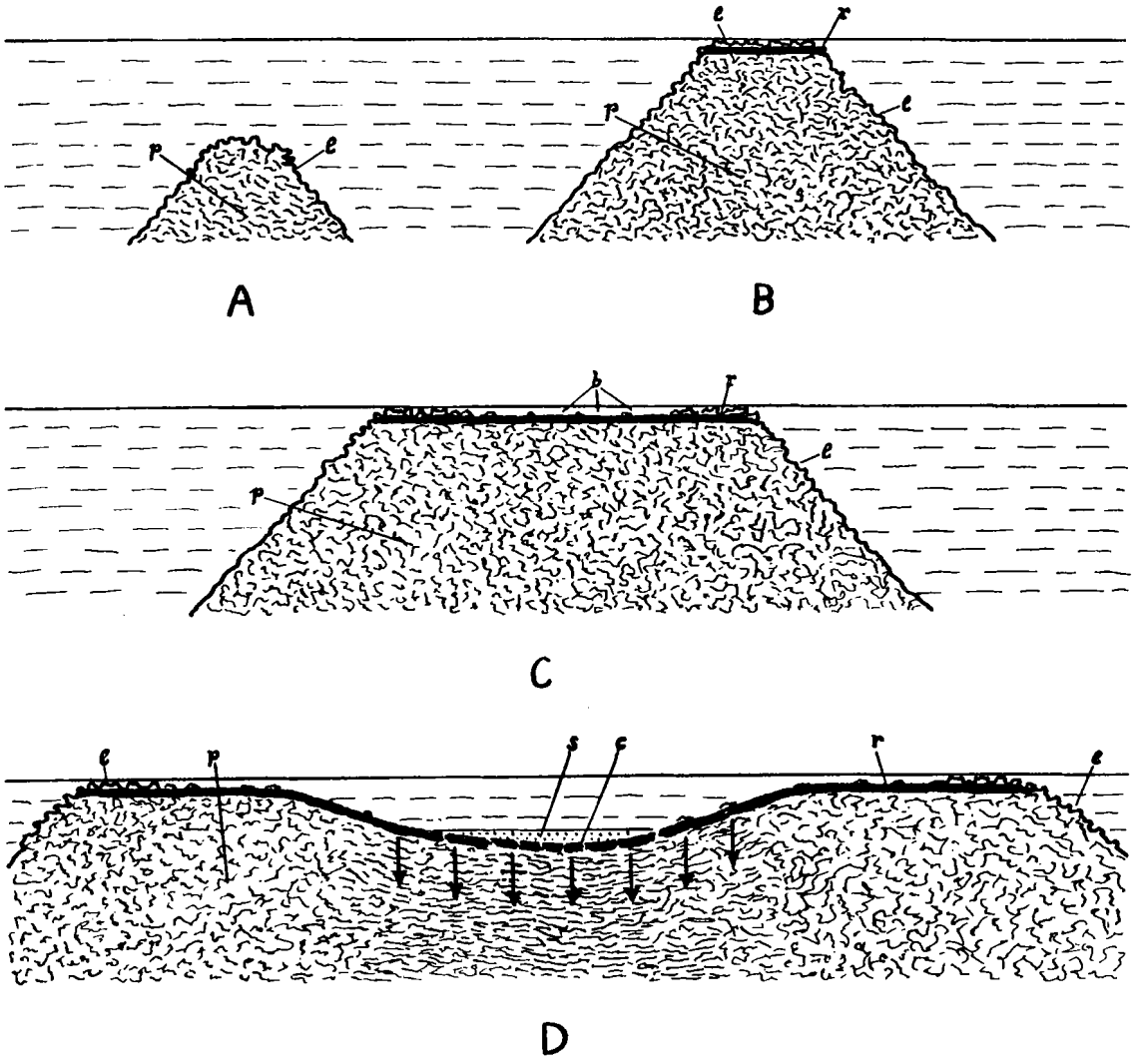

Fig. 10: Schematic sections through a reef gradually turning into an atoll. A) a cone-like reef grows toward the surface. B) Reaching the surface, the reef forms a solid reef flat. C) Reef and reef flat extend outwards, the center of the platform gets barren and covered with sand. D) The reef has further increased in size and the platform subsides at the center.

l = living coral
p = porous structure
r = reef flat
b = barren area partly covered with sand
s = sand and gravel
c = central part of the platform which possibly disintegrates

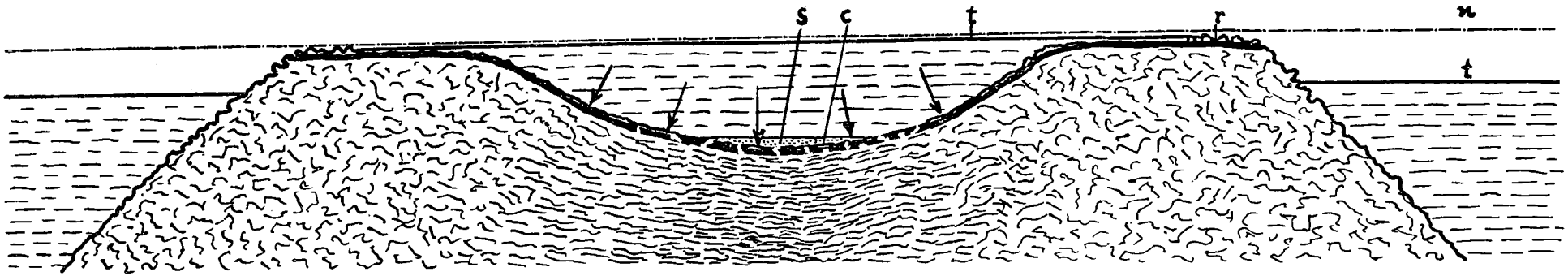

Fig. 11: Schematic section through an atoll showing the downward pressure of the water trapped at low tide.
n = normal sea level
t = sea level at low tide
r = reef flat
s = sand and gravel
c = central part of the platform which possibly disintegrates

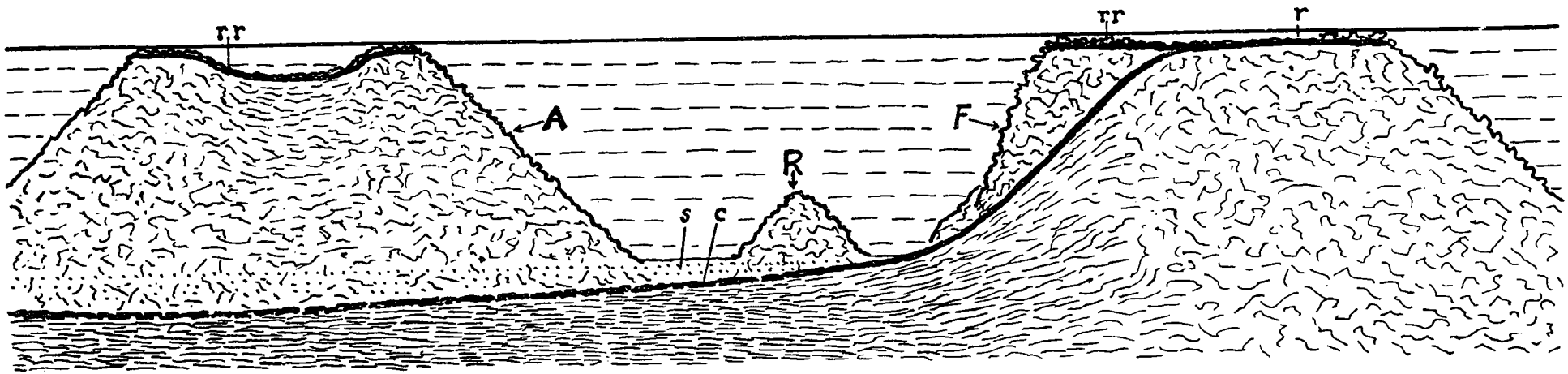

Fig. 12: Schematic section through one side of a larger atoll showing development of secondary fringing reef (F), secondary cone-like reef (R), and further development of such cone-like reef into a small secondary atoll within the large atoll (A).
r = reef flat
s = sand and gravel
c = central part of the platform which possibly disintegrates
rr = secondary reef flats