

Birth and growth of an Atoll

by
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With contributions by Messrs Demange and Granger.

This article summarises the most recent findings obtained in the world, including the results of work carried out by French geologists, particularly Messrs Demange and Granger.

On our Earth there are more than a thousand atolls or coral reefs (Fig. 1), lying between the tropics. In the Indo-Pacific region there are approximately 300 "genuine" atolls, according to the definition given by Mr J. Newhouse:

"An atoll is a living reef which is separated from the nearest land of volcanic origin by water having a depth greater than that at which hermatypic corals can grow."

What is an atoll?

Pacific atolls consist of two different structures one on top of the other: a volcano born on the ocean floor and which grew in size until its peak emerged some distance above the ocean surface, and a coral reef which succeeded in developing wherever it found a combination of favourable conditions, i.e., depths between 0 and 50 metres in clear and well-oxygenated waters.

We shall follow an atoll through the different stages of its formation and

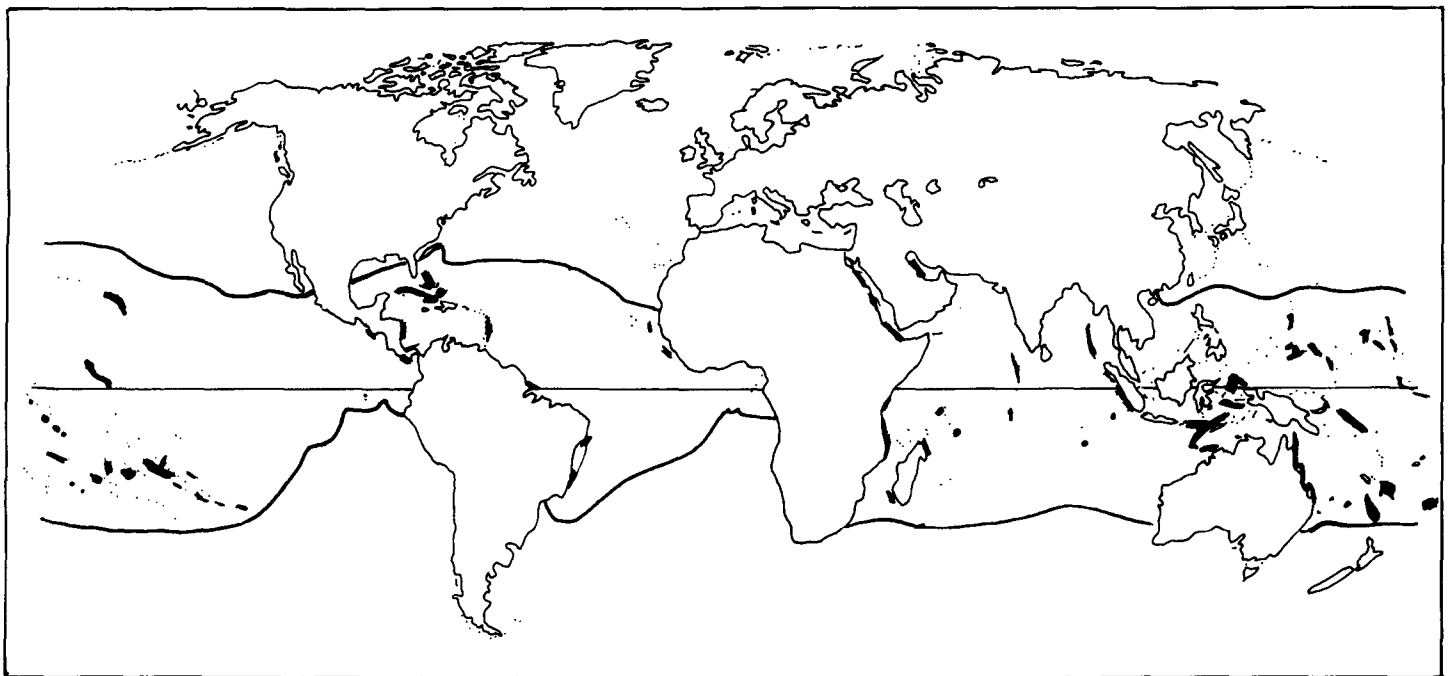


FIG. 1. Coral reefs and atolls lie in the intertropical zone.

study the factors which allowed it to develop: sea-level changes in the course of geological time, movements of the ocean floor, formative processes of submarine volcanoes.

A volcano foundation

Atolls originate as volcanoes on relatively flat ocean floors at depths between 4000 and 4500 metres. As a result of profound anomalies of the Earth's mantle and tectonic stresses which will be discussed further on, fractures occurred allowing flows of lava to well-up from the mantle and spread out over the ocean floor (Fig. 3). This action continued for some time and eventually aligned or random structures appeared along the fissures (Figs. 4 and 5). The flows accumulated to form a truncated flat-topped volcano called a guyot (Fig. 6). Its top sagged very slightly, but there was no crater.

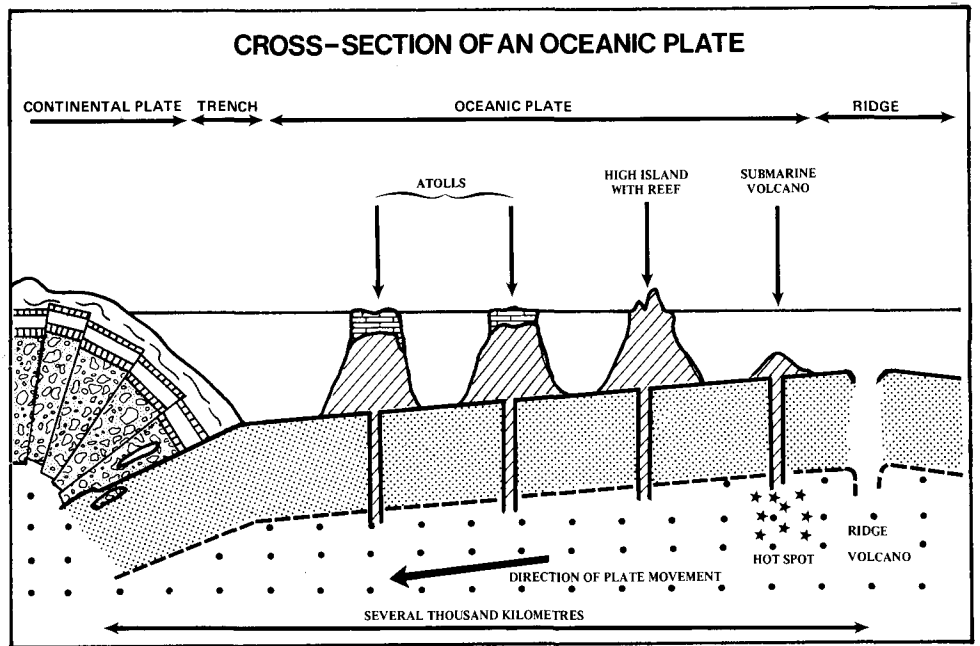


FIG. 2. Cross-section of an oceanic plate.

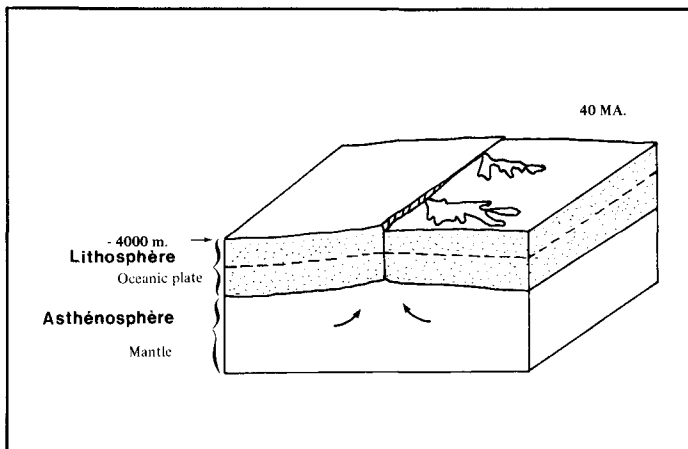


FIG. 3. Fracture of the plate.

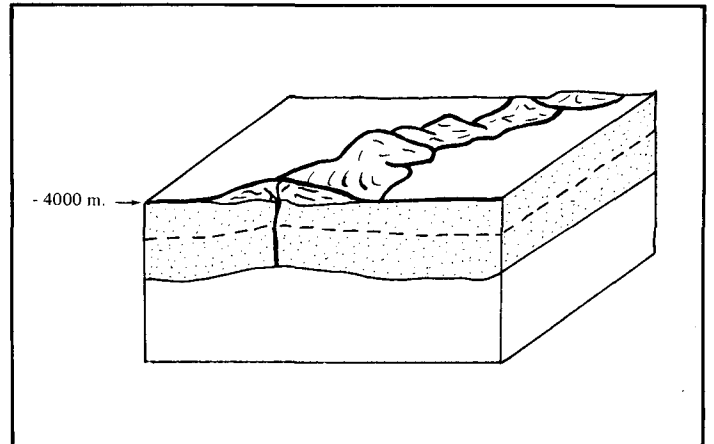


FIG. 4. Birth of the ridge.

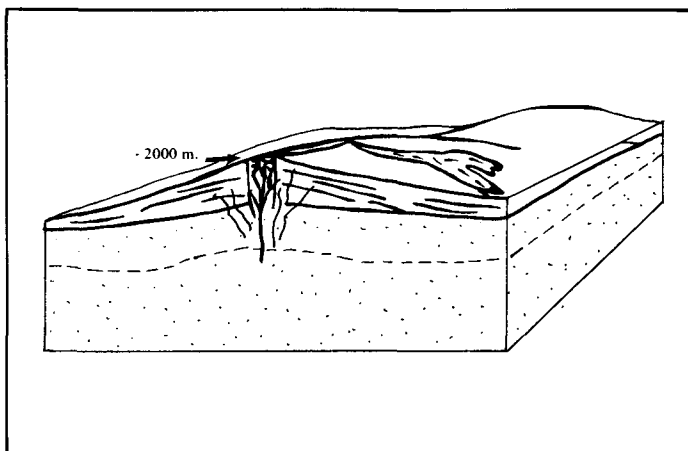


FIG. 5. Growth of the ridge.

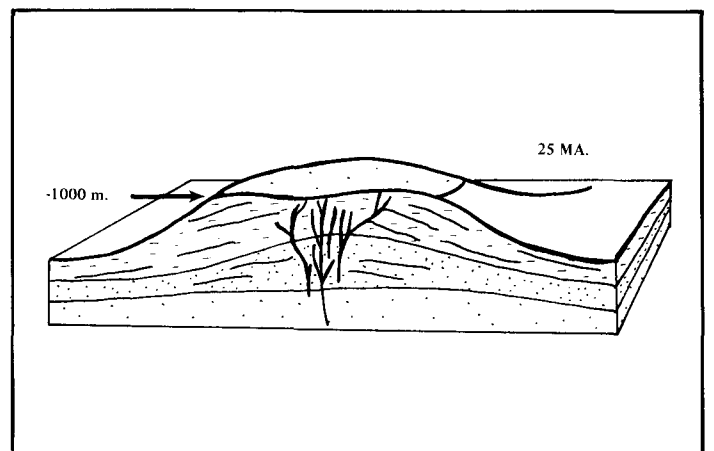


FIG. 6. Formation of a guyot.

The flows of lava continued to pour out through vertical intrusions called dykes that either occupied a radial position in the structure or were parallel to the fissures which had given birth to the volcano, and the volcano continued to grow. When it had reached a height of only some 200 metres from the surface, where the water pressure is no longer sufficient to prevent the release of the gases dissolved in the lava, the nature of the released products changed, the flows fragmented giving rise to autoclastic breccias, and the points of exit of the lavas (where the latter are degassed) became explosive and pulverised the lava into fine shards of glass (hyaloclastites).

When the volcano was almost level with the surface, i.e., about 8 million years ago, it appears to have had a great deal of difficulty in emerging since at that stage its lava supply was declining and erosion, mainly due to the action of waves on poorly consolidated materials, was causing it to grow in width rather than in height.

It finally emerged (Fig. 7) as a cone-shaped structure with slightly sloping sides (about 6° ; cf. Fig. 8). Its height could never have exceeded 600 metres above sea level. In the course of emergence, the central part collapsed, forming an elliptical caldera (kind of crater).

During the volcano's period of activity the ocean floor beneath it rose, probably as a result of pressures associated with the fusion process which generates the lavas, but as soon as the volcano died, it started sinking under its own weight, a phenomenon called subsidence which, in this area, proceeds at a rate of 1 cm per hundred years.

A coral top

Whenever conditions are right for coral establishment and growth – that is, while the volcano is emerging – the larvae of the corals contained in the plankton suspended in the sea water form scattered colonies on the volcano which begin to

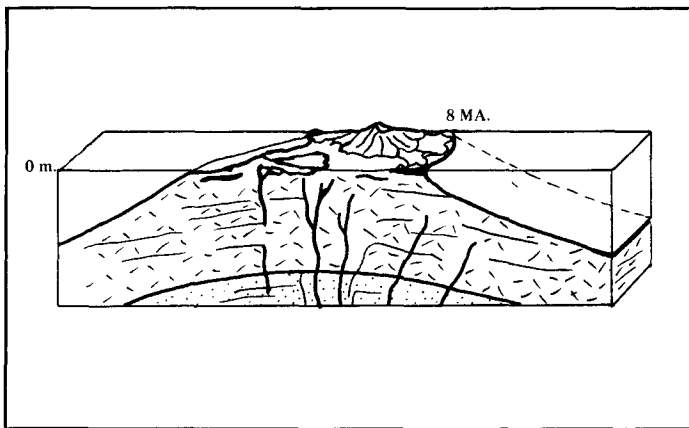


FIG. 7. Emergence.

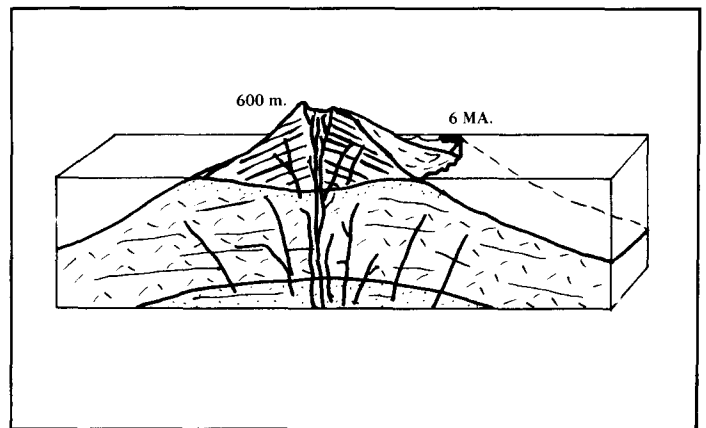


FIG. 8. Aerial volcanicity.

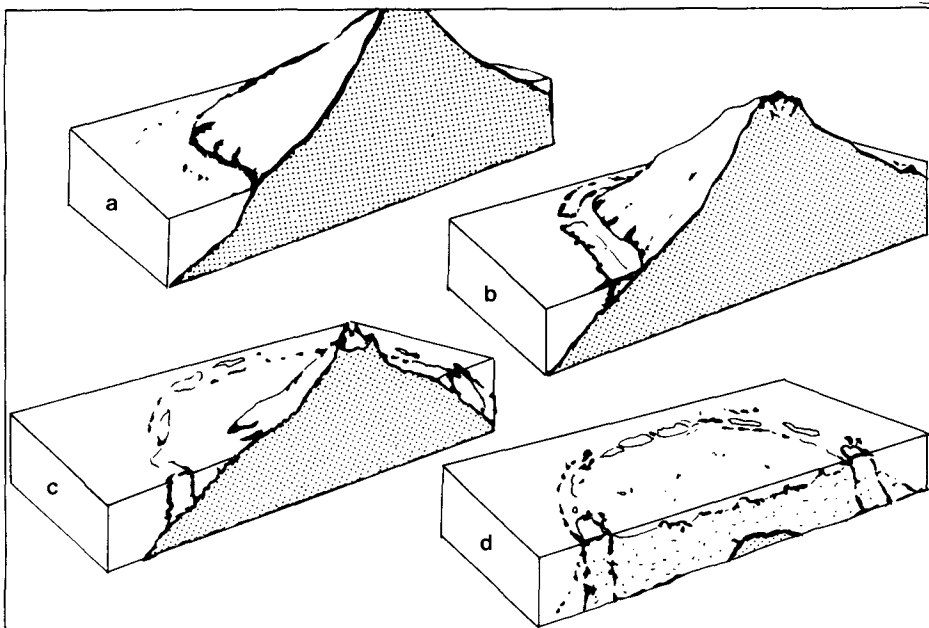


FIG. 9. Stages in the development of coral structures.

grow. Initial growth is impeded by falling ash from eruptions and mud from erosion of the sides.

Since the volcano is gradually subsiding, the corals are forced to grow in order to survive. They eventually form a ring (fringing reef stage) in the shape of the volcano when fully emerged, and small isolated growth zones on its sides (Fig. 9). This model is observable in Tahiti, with or without living coral along the coastline, a lagoon and a barrier reef.

As a result of subsidence and erosion, the volcano disappears under the water; it is, at this stage, completely covered with coral. Little by little the barrier reef restricts the circulation of water between the ocean and the lagoon to the "hoas" (passes) and in the lagoon sediments accumulate, allowing only a number of coral knolls to develop, after which coral growth continues mainly on the ocean side (Fig. 9d).

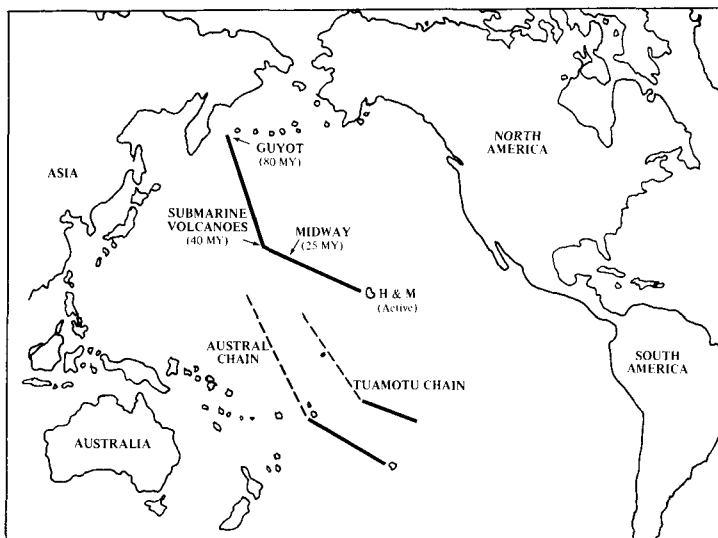


FIG. 10. Alignments originate above hot spots situated
 – for the Austral chain, near McDonald volcano;
 – for the Tuamotu chain, near Gala and Gomez;
 – for the Midway chain, in Hawaii.

Geological movements affecting atoll development

Now we have seen how an atoll is born and develops, we must place this process in the broader geological context of the Pacific Ocean and examine two phenomena that concurrently occur in our area: movements of the ocean floor and variations of ocean levels.

Movement of ocean floors

The development of the "plate tectonics" has focussed attention on certain parts of the world where plates are continuously being created or destroyed. We are located on a plate (Fig. 10) at the South Pacific ridge, which moves in a north-westerly direction at an average speed of approximately 10 cm per year towards a trench where it will be swallowed up. This speed, although high, is not sufficient to explain the origin of volcanic chains such as the Tuamotus (Fig. 11) by lava from the ridge. The youngest island in the chain (Ducie or Pitcairn) is situated at far too great a distance from the ridge to have been formed by it.

In 1970 Morgan proposed the theory of hot spots and mantle plumes to explain how island chains were formed a long way from the ridges. He postulates that in certain parts of the globe mantle anomalies exist which cause a partial fusion of the base of the plate that moves over them. Volcanoes are aligned in the direction in which the plate has moved in the course of successive geological periods, the oldest situated furthest from the mantle plume. The amount of lava pouring out of the mantle to feed and build up the volcano is therefore very great when it is first formed on the plume, but decreases rapidly as the plate moves on.

This phase of decreased feeding explains why the volcano has considerable difficulty in breaking through the water surface. Growth ceases at this stage and subsidence begins.

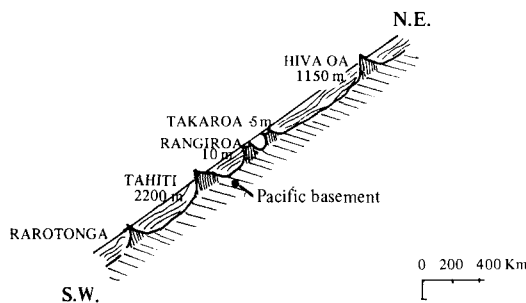
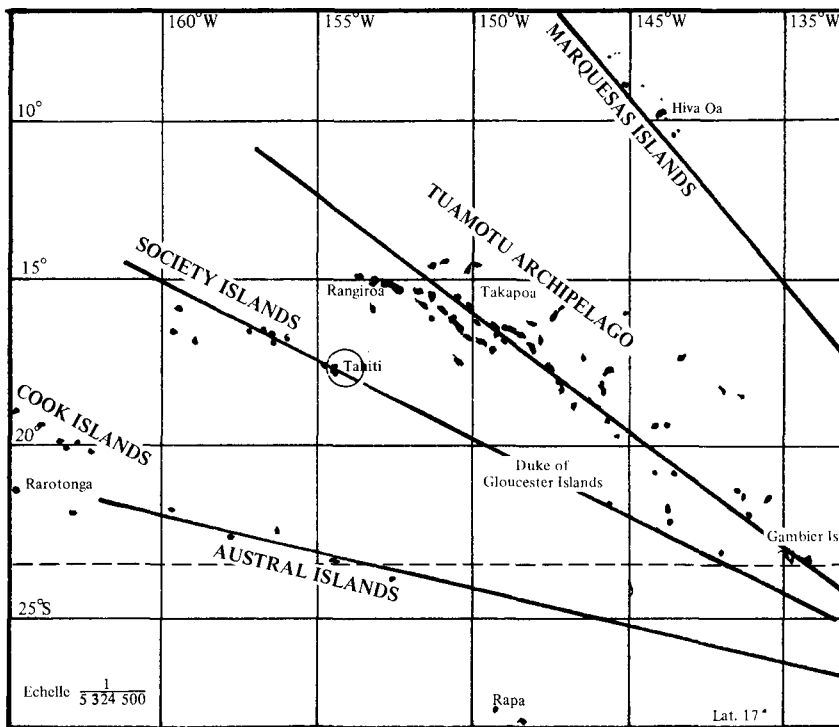


FIG. 11. Alignment of archipelagos.

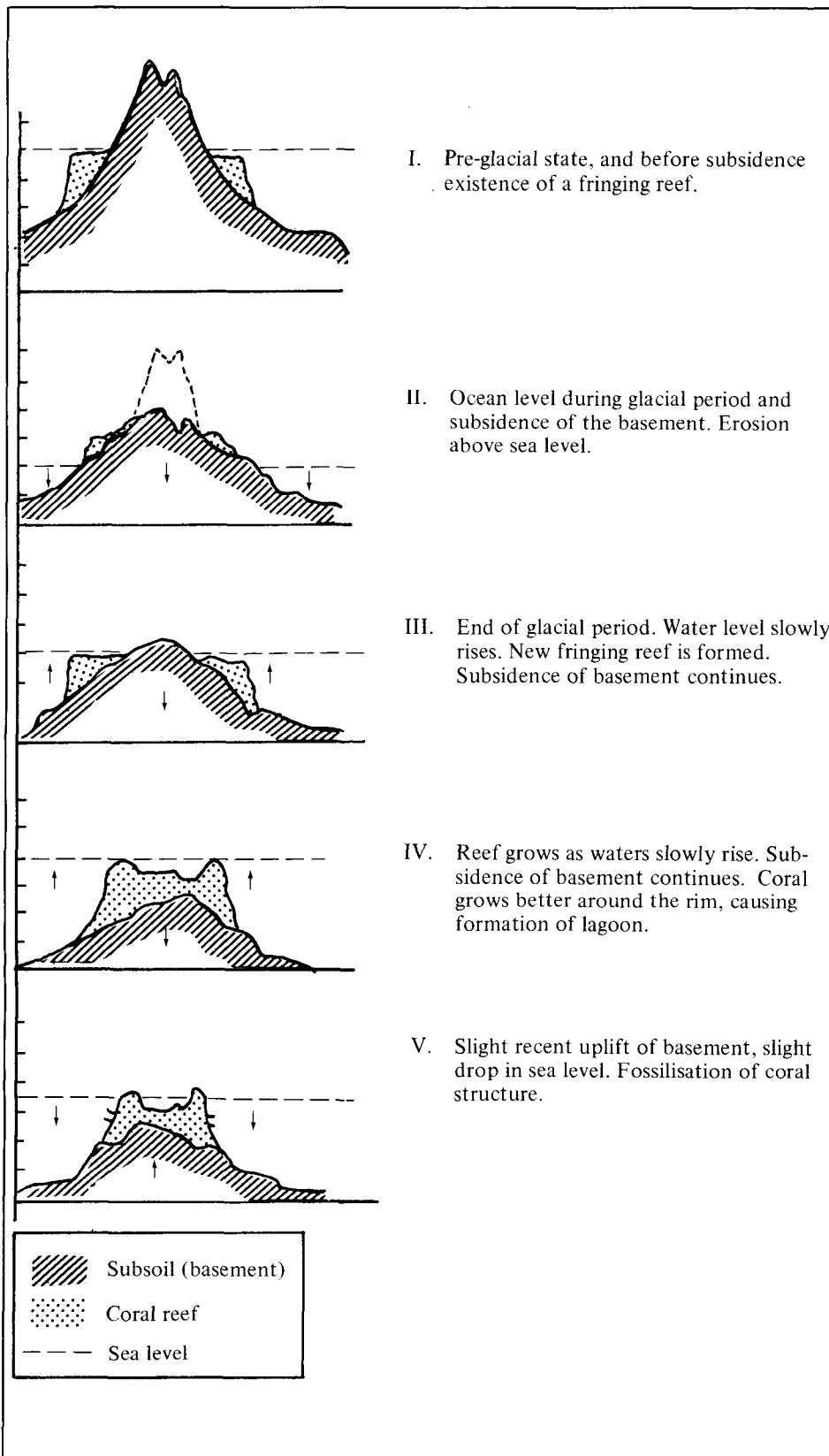


FIG. 12. Development of an atoll according to the combined theories of Darwin and Daly, supplemented by Sylvester and Ranson. (N.B. This development, which corresponds to Würm's glaciation, may have occurred several times in the geological history of the Earth).

Sea-level changes

Variations of the sea level (Fig. 12) during the Quaternary period (in the last two million years) are well understood. For the earlier periods, data are rather unreliable. The mechanism of these variations is related to the extension or reduction of the polar ice caps. During the reduction phase the ice melts, the sea level rises, and the reverse occurs during the extension phase.

These variations caused atolls to emerge more than 50 metres above the water surface. During emergences, and more generally on motus, rainwater can infiltrate and form layers and lenses of fresh water. A chemical reaction occurs where the fresh water meets the sea water contained in the sub-soil, calcium carbonate (limestone) being converted into carbonate of calcium and magnesium (dolomite). The coral skeleton is made up of aragonite* (Ca CO_3) which, when the coral dies, is transformed into calcite* (Ca CO_3). Rainwater seeping through the limestone dissolves part of the carbonate. When the fresh water containing Ca CO_3 reacts with sea water containing magnesium salts, dolomite, $\text{Ca Mg (CO}_3)_2$, is precipitated out.

This is one of the processes by which dolomites are formed. The entire base of coral formations is thus converted into dolomite, giving a much denser rock.

During each emergence corals in the upper portion are fossilised and indurated. We discovered indurated foliations corresponding to known glacial periods at depths of -2, -11, -23, -44 and -66 m.

Thus an atoll is created by a volcano, which itself is formed by the passage of a plate over a mantle plume. As soon as the volcano moves away from the mantle plume, it is no longer fed with magma, dies and begins to subside. Corals then colonise it according to variations of sea level. The thickest coral formations are found furthest from the mantle plume: 350 metres south-east of the Tuamotus, 600 metres at Hao, 1000 metres at Rangiroa.

It remains to be explained why some atolls which were level with the sea surface now project as high as 70 metres above the water (Makatea).

In March 1978 the Americans McNutt and Menard put forward a clear and

* Aragonite - stable form of calcium carbonate at high temperature and pressure.

* Calcite - stable form of calcium carbonate at normal temperature and pressure.

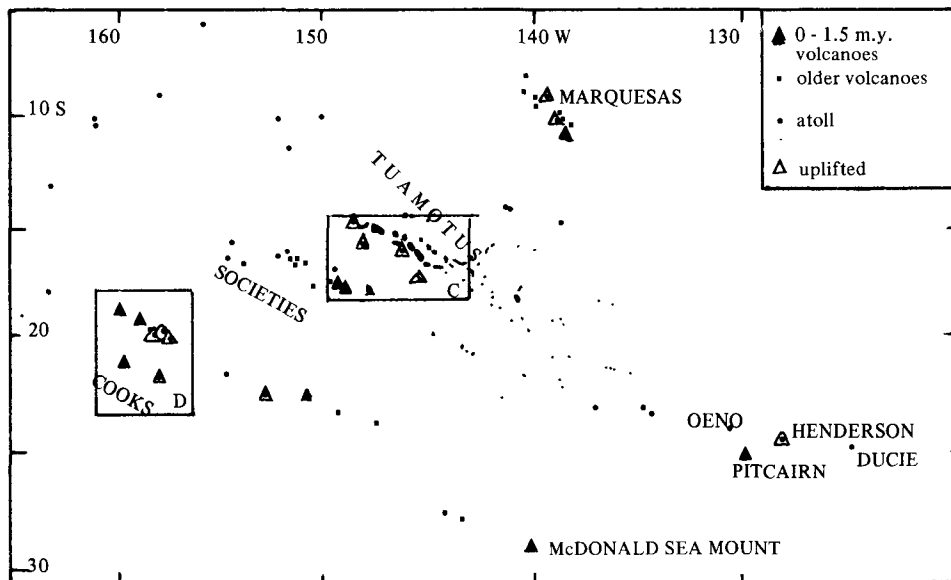


FIG. 13(a). Locations of elevated atolls, sea-level atolls, and active or recently active volcanoes in the equatorial Pacific. Outlined areas show the locations for the islands in Figs. 13(c) and 13(d).

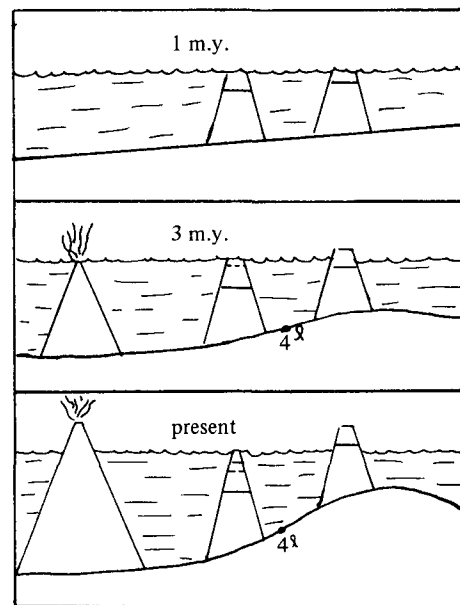


FIG. 13(b). Model of apparent sea-level change on coral atolls caused by volcanic loading on an elastic lithosphere. Q is the flexural parameter which depends on the lithospheric flexural rigidity.

attractive theory. Glacial eustatism (i.e., oscillation of the sea level in glacial time) cannot account for the simultaneous existence of elevated atolls and atolls at sea level. The fact that active or recent volcanoes have been found close to elevated atolls suggests that they were raised tectonically by volcanic loading.

The physical model which explains regional deformations is based on the

hypothesis that the upper part of the lithosphere acts like an elastic envelope enclosing an incompressible fluid. When this elastic envelope is stretched taut, any weight on it is distributed over a far greater area than that of the actual load zone. As a volcano grows in size it therefore deforms the ocean basement and affects the apparent level of the ocean for neighbouring coral atolls.

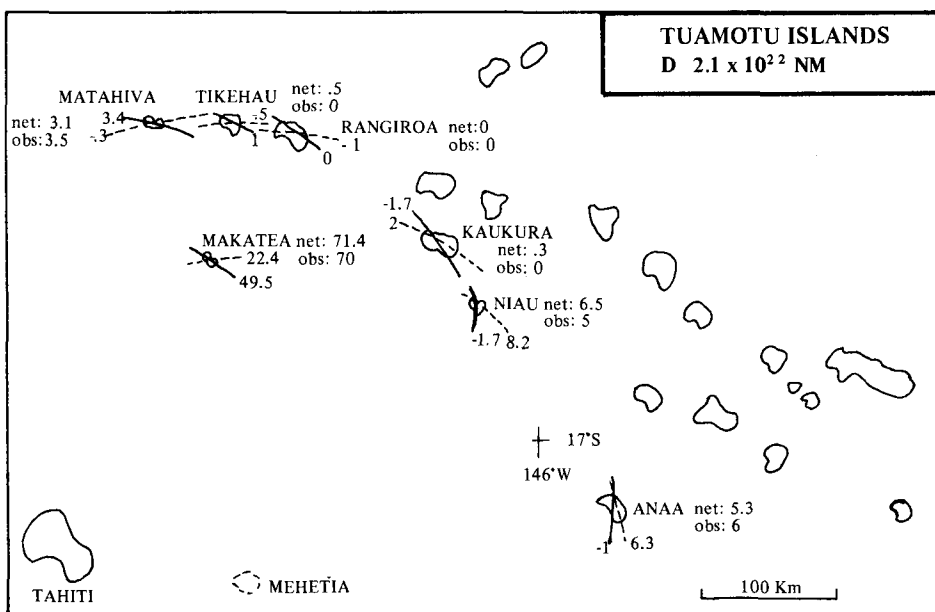


FIG. 13(c). Atoll uplift in the Tuamotu Islands. Uplift contours drawn through atolls correspond to the predicted flexure from loading by Tahiti (solid arcs) and Mehetia (dashed arcs). The theoretical sum is compared to the observed elevation.

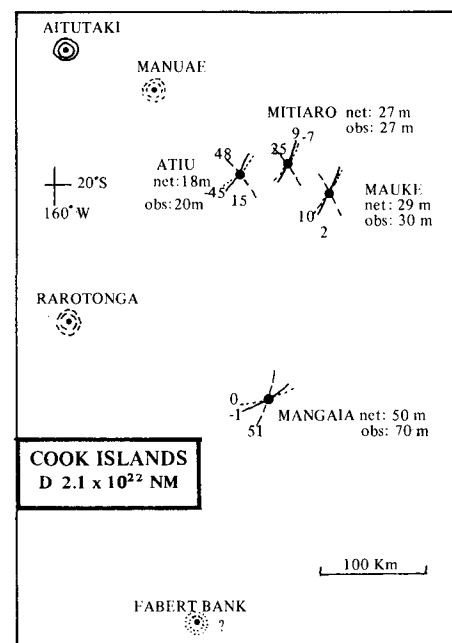


FIG. 13(d). Uplift contours keyed to three volcanoes are drawn through four atolls in the Cook Islands. For each atoll the resulting sum from the theoretical uplift is compared to the observed uplift. Although Fabert Bank was not included in the calculation, it may also elevate Mangaia.

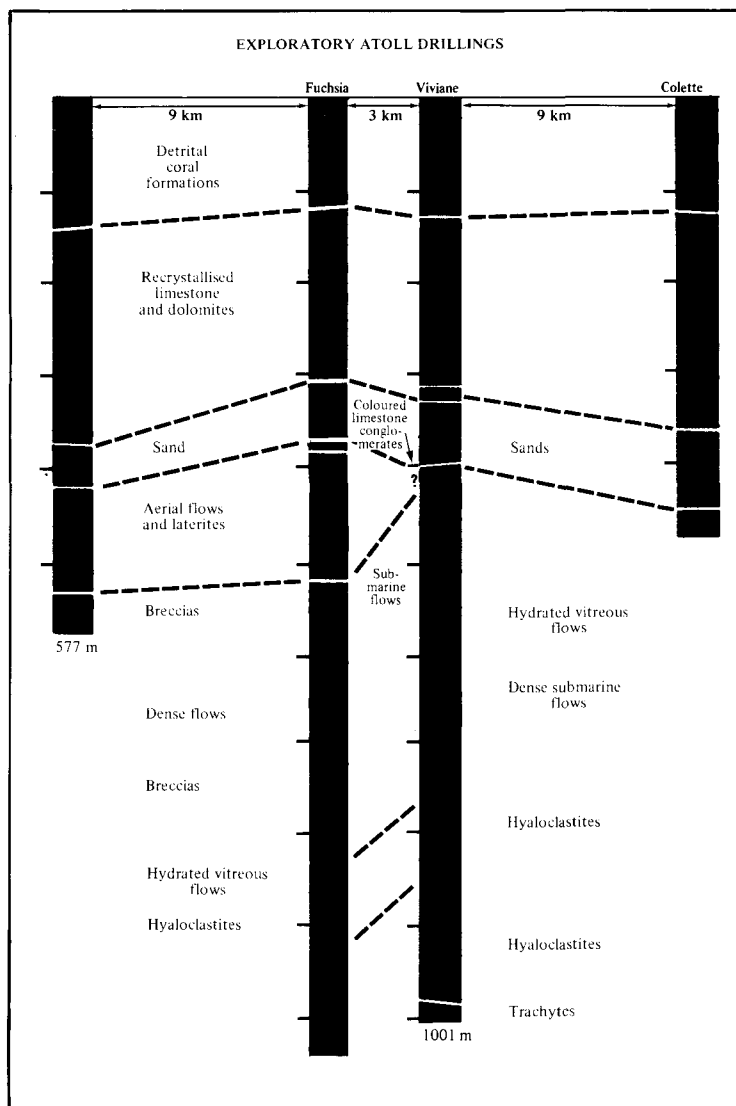


FIG. 14.

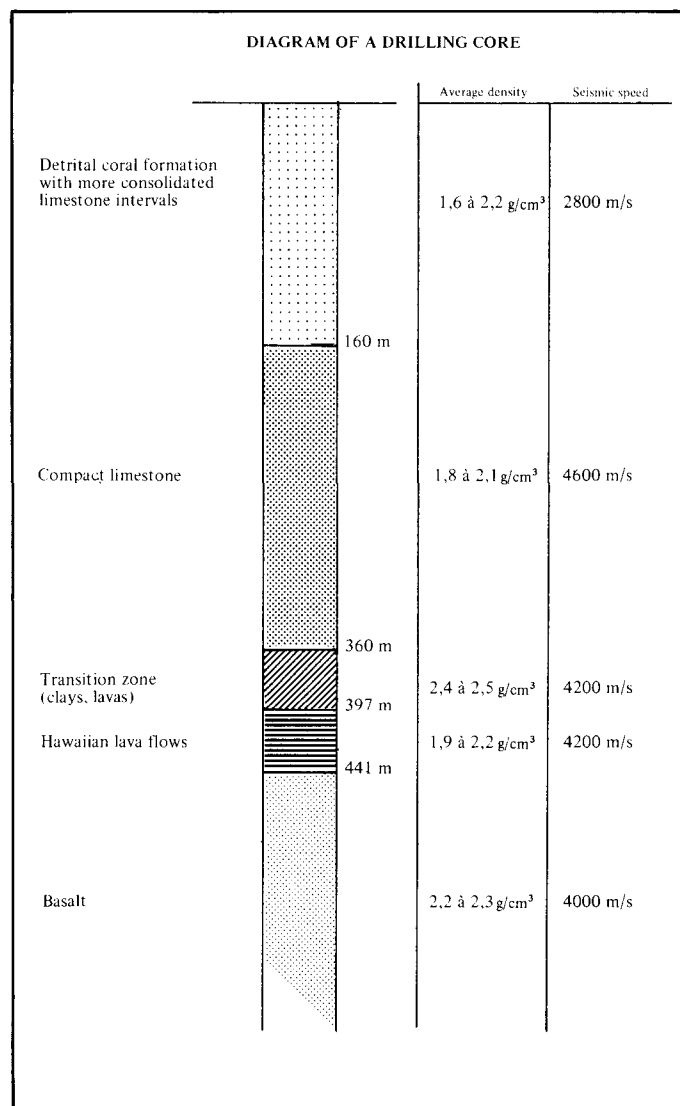


FIG. 15.

Using this theory, Menard was able to explain with remarkable precision the uplift of Makatea by the weight of Tahiti and Mehetia and the elevation of Atiu, Mitiaro, Mauke and Mangaia in the Cook Islands by loading from Rarotonga, Aitutaki and Manuae (Fig. 13).

What evidence is there to substantiate these hypotheses?

I shall not go into the plate tectonics theory, now generally accepted as a result of the *Glomar Challenger* expeditions and the Cyanheat operation which made it possible to observe the rift in different places along its 60,000-km length and the subduction zone where the African plate dips under the European continent.

To conclude, I shall simply give the results of drillings conducted in various places on one of the Tuamotu atolls,

illustrating them by a series of cores (of diagrams Fig. 14) which feature (from top to bottom):

- indurated coral surface layer.
- calcaranites.
- indurated dolomites.
- chalky dolomites.
- coloured dolomites.
- a transition zone containing detrital materials from the emerged volcanic sea mount:
 - volcanic scoriae.
 - clays.
 - river pebbles.
- aphyric basalt flows resulting from aerial volcanicity.
- hyaloclastites.
- autoclastic breccias.
- dense, vitreous basalt from dykes.

□ □ □

Jan Newhouse, author of the four articles:

- *What is an Atoll?*
- *Water Desalination for Atoll Agriculture*
- *Marine and Terrestrial Flora of Atolls*
- *Energy*

which appeared in the SPC Bulletin 3Q '80 has duties with:

- The Department of General Science and the Pacific Island Studies Program, University of Hawaii, and
- Ecole Pratique des Hautes Etudes, National Museum of Natural History, Paris.