OPEN OCEANS

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Summary

The ocean environment is the most likely place where life originated on Earth. The open ocean, exhibiting similar basic parameters (extent, rate of paleogeographic changes, depth) as those of the recent ocean, has been developing for roughly 2.5 Ga of Earth's existence. The distribution and configuration of continents are the basic elements

controlling the ocean shape, direction of sea currents, temperature, and salinity, and consequently the conditions for life. The distribution and configuration of continents has undergone change with geological time due to plate tectonics and continental drift. If the continents are arranged mostly in a meridian direction (as they are nowadays), then colder periods begin to occur, together with glaciation of polar regions. The influence of orbital cycles on Earth's ecosystem is strengthened during these cold periods. Changes in temperature and water circulation considerably affect the productivity of oceans, and consequently the entire Earth system. Deep-sea sediments are an excellent source of information on the paleoclimate and the general state of life-support systems on Earth approximately from the middle part of the Mesozoic until the Quaternary. The oceanic waters represent a huge, very important, and fast-reacting reservoir of many chemical elements and compounds including CO_2.

1. Basic Parameters and Functions of Oceans

1.1 Formation of Ocean Basins—Plate Tectonics

Plate tectonics is the basic geotectonic process controlling the formation of ocean basins. The theory of plate tectonics unifies the continental drift and the sea-floor spreading theories (see *Plate Tectonics*).

Plate tectonics is believed to have functioned since the beginning of the Proterozoic (2500–2000 Ma) in a form not much different from the present-day plate tectonic movements. At the start of the Proterozoic, the majority of radioactive elements that existed during Earth's origin ceased to emanate heat, which led to a decrease in heat production and a deceleration of Earth's dynamics. The originally small, unstable, rigid forms of continents started to merge into plates whose areal extent was of the order of some tens of millions of square kilometers. Most of the present continental crust (90%) originated during the initial phase of plate tectonic functioning.

The consolidation of continental blocks led, at the same time, to separation of space for the formation of ocean basins. The basins occurred above the oceanic crust, which, in contrast to the continental crust, still continues to build up along mid-ocean ridges. The ridges lie over the rising parts of convection currents in Earth's mantle. These currents carry oceanic crust away from the ridges; this pulling apart forms cracks in the graben at the ridge crest, which are filled by basaltic lava, thereby forming a new oceanic crust. Oceanic crust is being destroyed in marginal trenches along which one plate is subducted under another plate. The oldest oceanic crust preserved *in situ* is of Lower Jurassic (200 Ma). Any older oceanic crust has either already been subducted, or forms small questionable relicts in highly metamorphic complexes. In this way, the ocean floor is continually recycled (see *Wilson cycle* in *Proterozoic History*).

Converging lithospheric plates create, in all, three types of boundary, each of which exhibits specific features. If one segment of oceanic crust converges with another, one plate is subducted while the other plate is moved over the first one. This type of boundary is characterized by an ocean trench, and by volcanoes on the overriding plate. If oceanic crust and continental crust converge, the heavier ocean plate is subducted and the lighter continental plate overrides it. In such a case, the trench structure and volcanism are accompanied by coastal mountain ranges built of sediments pushed up from the trench. In the case of collision of two blocks of continental crust, no plate subducts; the result is an orogenic process, as can be seen nowadays in the Himalayas.

Consequently, plate tectonic movements are responsible for the shape and distribution of basic elements of the ocean floor—ocean ridges with rift valleys, submerged volcanoes and guyots, large flat ocean basins, ocean trenches, and continental slopes. The relatively fast movement of lithospheric plates (on the order of centimeters per year) leads to gradual changes in the configuration of ocean basins. The rise and destruction of the link between continents led many times during Earth's history to an overall reorganization of sea current systems, which had considerable impacts on Earth's ecosystem.

1.2. Chemical Composition of Seawater

During the entire evolution of Earth, atmospheric and surficial waters transported and discharged into the ocean a vast amount of salts leached from weathered rocks. Other sources of salts are deposits of volcanic material washed down into the sea, and submarine volcanic activity. The chemistry of seawater is also influenced by gases dissolved in atmospheric precipitates. Among these, oxygen and carbon dioxide play a crucial role in ocean ecosystems.

Both the salinity and content of gases in seawater have undergone considerable change during the geological history of Earth, depending on the interaction with biota, on the configuration of basins and adjacent continents and also on changes in temperature due to cosmic phenomena (particularly solar cycles). The present deep ocean water shows stable salinity equal to about 35‰ of which ~75% consists of NaCl. The rest comprises other chlorides, iodides, carbonates, etc. The salinity increases through evaporation and ice freezing. Thus, the salinity in surficial parts of the ocean in the tropics may reach as much as 41‰. Glaciations have played an important role in increasing the salinity of seawater during Earth's history. Glaciations led to a fall in sea level and removal of salt from the system in the form of evaporates which were deposited in isolated parts of the sea. The Upper Permian period is believed to have played an important role in increasing the salinity of water and deposition of evaporates, because large basins were isolated during formation of the Pangea supercontinent.

The occurrence of carbonates and hydrogen carbonates, silica, components of nitrogen, phosphorus, and sulfur is very important for ocean ecosystems. Local and temporal variability in parameters of these components has a crucial importance for the productivity of ecosystems (see Section 1.4.).

1.3. Circulation of Seawater

The volume of material transported through circulation of seawater exceeds by several orders of magnitude the volume carried by rivers. Insolation and rotation of Earth cause and influence the circulation of water in oceans, similar to atmospheric circulation. The present state of circulation of seawater resulted from a nonrecurring configuration of the continents, the insolation regime and the inertia of earlier processes. Nevertheless, knowledge of the physical preconditions of circulation (which is summarized in what is called Ekman's model) allows us to reconstruct the major directions of seawater circulation and their impact on ocean ecosystems in geological history.

1.3.1. Surface Ocean Circulation

Prevailing winds develop waves and consequently surface ocean currents. This effect products equatorial currents of east–west direction and mid-latitude easterly currents of west–east course. This surface ocean circulation would flow around the globe for a limitless time if there were no continents to block the movement. However, due to the existence of continents, some circular currents (gyres) originate. The situation becomes even more complex when taking into consideration the effect of the Coriolis force. Ocean currents moving north or south in the Northern Hemisphere are deflected to the right by the Coriolis force, forming Ekman spirals. The consequence of Ekman spirals is a change in the direction of currents with increasing water depth. As a result of the Coriolis force, in the Northern Hemisphere, equatorial easterly winds push surface water to the west and north while the mid-latitude western winds develop a movement of water masses to the east and south. Consequently, water in the Northern Hemisphere circulates in a clockwise direction, whereas in the Southern Hemisphere, it circulates in an anticlockwise direction. The water flows into the central part of huge water maelstroms (domes) in which it creates overpressure that works against the Coriolis force.

The phenomena described above create in the Northern Hemisphere western boundary currents (Figure 1) (of which the Gulf Stream is an example) along western continental margins, and eastern boundary currents, which are deflected towards the right (in the Northern Hemisphere) at continental barriers. Because of the asymmetry of maelstroms (due to the Coriolis force), the eastern boundary currents are wider, slower, and shallower than the western boundary currents.

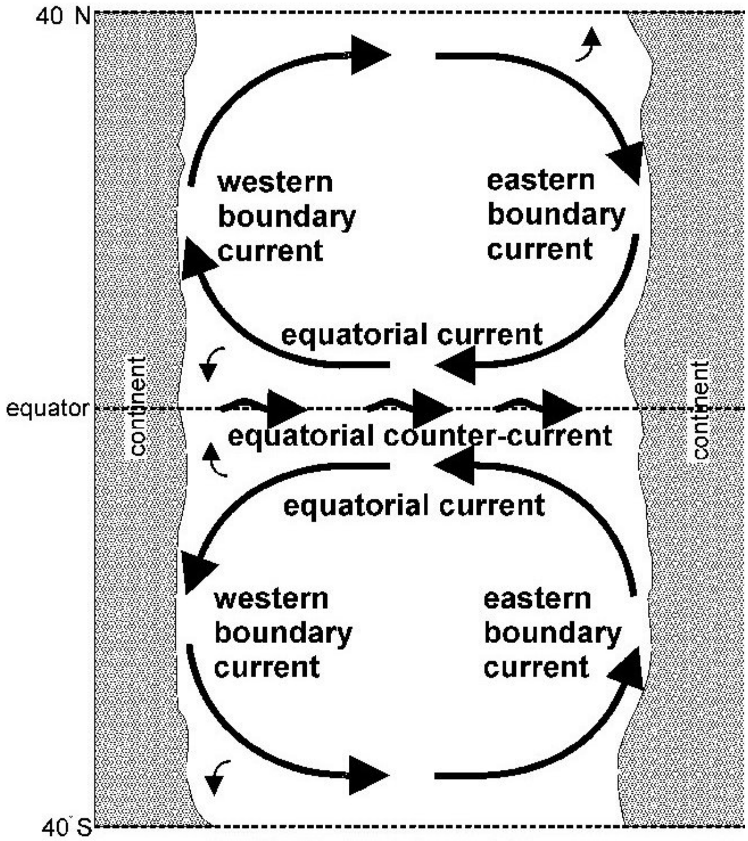

Figure 1. Simplified scheme of surface ocean circulation

1.3.2. Upwelling

In places where currents move away from each other, the deep ocean water is drawn in towards the surface. This ascending current is rich in nutrients, thus allowing abundant plankton to develop in the upper sea zone. The most important global fisheries are related to upwelling zones.

1.3.3. Deep Ocean Circulation

Deep-sea currents supplied with cool heavier water from polar regions descend below the warmer and lighter water of lower geographic latitudes. This deep circulation is triggered by differences in water density caused by diversity in water temperature and salinity; it is therefore often called thermohaline circulation. This circulation primarily affects water in the deep oceans below the zone of surface-ocean circulation. It produces nutrient-rich waters that rise to the surface during upwelling. At present, North Atlantic deep water is formed by cooling relatively saline surface water between Greenland and Great Britain; Antarctic bottom water forms along the continental shelf of Antarctica. Its density increases as salts are expelled from the freezing ice. The Antarctic Bottom Water is the densest water mass in the oceans and it fills most of the southern Atlantic, Pacific, and Indian Oceans (see *Climate in the Quaternary*).

1.4. Open-ocean Ecosystems

The major producer of organic matter in the ocean is phytoplankton—microscopic organisms capable of photosynthesis. Among the phytoplankton, the most important organisms are blue-green algae, diatoms, silicoflagellates, and coccolithophores. These organisms are limited to the photic zone of the world's oceans and mainly occur in the upper part of that zone (termed the euphotic zone). The growth rates of these organisms are influenced by temperature, light, and nutrient supply. The main nutrients are represented by phosphates (PO^{4-}), nitrates (NO^{3-}), ammonia (NH_3), and silica (SiO_2).

Tiny planktonic heterotrophic organisms that consume phytoplankton are called zooplankton. Foraminifers (unicellular protozoa with a carbonate shell), radiolaria (protozoa with a silicate shell), and finally tiny arthropods are the most prominent constituents of zooplankton in the present seas.

The nekton consists of larger organisms capable of active movement in a water column. The majority of nekton are predators which actively hunt other organisms or filtrators which strain water and catch small organisms. Fish is the most abundant constituent of the present nekton, while mammals are represented by whales, seals, sea otters, sea lions, and a few others. Among reptiles, sea turtles are of some importance.

Nektonic assemblages are most abundant in the photic zone, although carnivorous nekton may occur in sporadic amounts down to a depth of several kilometers. Forms specialized for the aphotic zone often exhibit bizarre body shapes, and use their light organs for communication and/or for hunting (e.g., deuce fish). Nektonic organisms reveal very interesting life strategies and behaviors (e.g., tiny fish hunting in shoals).

The benthos occupies the bottom surface or subsurface. Depths typical of the bottom of ocean basins (i.e., several kilometers) are characterized by conditions controlled by high hydrostatic pressure, absence of light, coldness (–1 °C to +5 °C), stable salinity around 35‰, and low concentration of organic matter. The majority of organic matter has already decayed during the fall of dead organisms through the water column. The content of organic matter in sediment is locally influenced by currents (which may be relatively strong), by the productivity of the ocean and by the distance from the shore. The so-called epibenthos lives on the floor/bottom surface. It includes, for instance, brittle stars, sea urchins, sea slugs, and crabs; most epibenthic organisms are scavengers or sediment feeders. The in-fauna (organisms living inside the substrate, e.g., worms, molluscs) comprises sediment-eaters and filtrators that build a complex system of tiny channels and cavities inside the sediment and on its surface. "Teams" of bacteria, among which occur endosymbionts of, for instance, pelecypods and annelids, contribute greatly to the utilization of the very limited nutrient potential of the deep-sea bottom.

1.4.1. Hydrothermal Vent Communities

Along mid-ocean ridges and in volcanic areas, exceptional ecosystems have been identified that are based on chemosynthetic (not photosynthetic) primary producers (i.e., bacteria). They take nutrients from the vents and are able to live in extremely hot water.

The dominant life forms representing the upper trophic level are giant worms (several meters long!) and bivalves, some of which have endosymbiotic bacteria (see *Origin of Life*).

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Biographical Sketch

Radek Mikuláš (born 1964) is a senior researcher of the Institute of Geology, Academy of Sciences of the Czech Republic, Prague. His professional experience includes a study of trace fossils in a variety of sedimentary environments (deep marine, shallow marine, freshwater, subaerial), aspects of fossil behavior (burrows, borings, plant trace fossils), contexts of geological record (ichnological record of extinctions and recovery, basin analysis) and age (Palaeozoic, Mesozoic, modern).

He entered the Institute of Geology, then Czechoslovak Academy of Science, as assistant in 1987. In the same institute he elaborated his PhD. study "Trace fossils of the Bohemian Ordovician" (1991). His professional experience outside the Czech Republic includes the study of trace fossils in the Ordovician of Spain (1992), a postdoctoral fellowship at the Department of the Earth Sciences, University of Liverpool (supervisor Dr. T.P. Crimes), and a re-study of trace fossils from the Jurassic of Greenland (1997; University of Copenhagen).

His recent undertaken research projects include:

Since 2000: Grant by The Grant Agency of the Czech Republic, "A multidisciplinary research of the locality Dětaň (Oligocene, Doupov Mountains: integration of palaeontology and pedology" (principal investigator).

Since 2000: Grant by The Grant Agency of the Czech Republic, "Facies Architecture of the turbidite system of Moravice Formation, Nízký Jeseník Culm Basin, based on sedimentology and ichnofacies analysis" (co-investigator).

1998–1999: UNESCO-IGCP Project #410 "The Great Ordovician Biodiversification Event: Implication for Global Correlation and Resources" (member of the national working group)

1999: PalSIRP (USA) Grant: A systematic revision of the ichnotaxa erected in "Problematica Silurica" by A. Fritsch (1908; in J. Barrande et al.: Systeme Silurien).

1995–1997: UNESCO-IGCP Project #335 "Biotic Recoveries from Mass Extinctions" (member of the national working group).

1998: PalSIRP (USA) grant: Terrestrial Bioerosion and its ichnological consequences.