difference is largely due to salt content, we call the boundary a *halocline*. A *pycnocline* is the boundary between two water masses with different densities, without a specified cause. Lakes in temperate and cold regions have good circulation. This is due to water attaining maximum density at 4°C, below which temperature density inversion causes turnover.

The addition of freshwater to a basin (e.g. Baltic Sea, Black Sea) also leads to stratification of the water due to salt concentration because brackish water flows on top of marine water with higher salinity. Evaporite basins produce water which is heavy due to its high salt content and therefore forms a layer which flows along the bottom. If a salinity stratification becomes established, it will weaken or destroy the circulation and lead to reducing conditions in the bottom layer. If the density contrast due to salt concentration is greater than that due to temperature, this will impede or prevent the downward flow of cold, oxygen-rich surface water (Fig. 3.16).

There are indications that in previous geological periods (e.g. the Cretaceous) the bottom water in the ocean basins was warm, salty water (about 15°C) compared with the present situation with cold basal water (2–3°) and a normal salinity. A higher average temperature in the oceans leads to reduced CO_2 solubility and a deeper carbonate compensation depth (CCD). The volume of water welling up from deeper water layers to the surface corresponds to the amount of downflow. If we have basal water with high salinity, the reduced density contrast results in less downward flow and consequently less upwelling, so less nutrients are added to the surface water.

We have seen that a number of different processes control the geochemical equilibrium of the ocean. There must also be an equilibrium between the addition and removal of chemical components for the ocean water composition to remain relatively constant. The conditions in which this equilibrium was maintained, however, have varied through geological time. During the first part of the Earth's history, up to about 2.5 billion years ago, the atmosphere was reducing. Most geochemical processes acted very differently then from the way they do now. Weathering was less

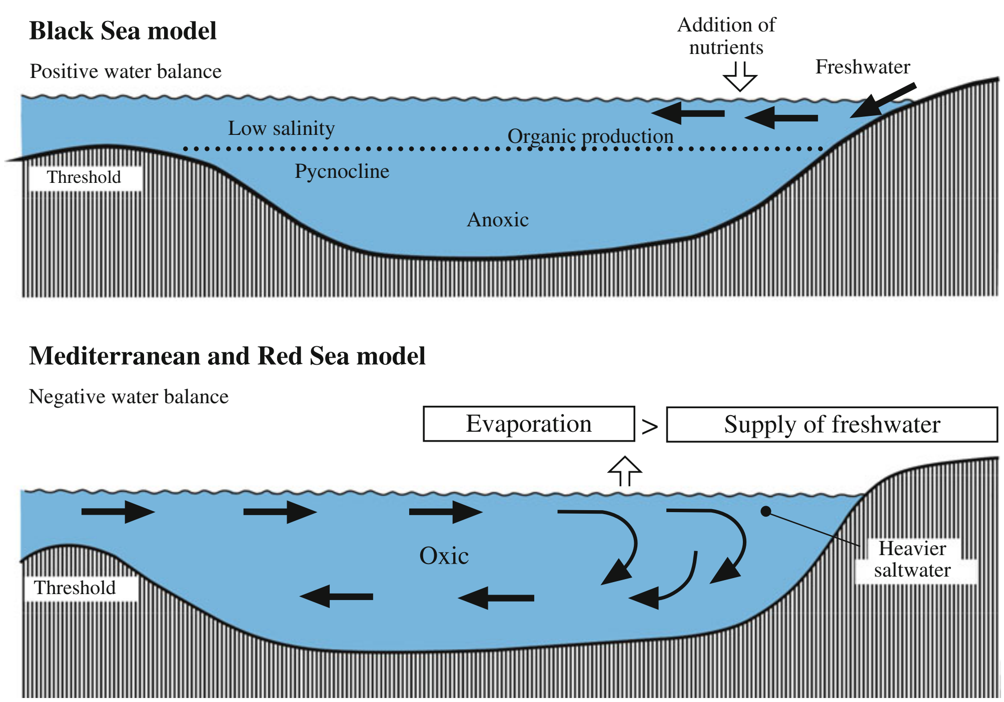

Fig. 3.16 Circulation of water in basins with a surplus of freshwater input compared to evaporation (Black Sea model). This results in poor vertical circulation and anoxic (reducing) bottom waters. The Mediterranean and Red Sea model represents excess evaporation compared to freshwater input. The surface water will then have the highest salinity and density and sink to the bottom. This increases the vertical circulation and helps to maintain oxic conditions

efficient because of the low oxygen concentration in the atmosphere and limited biological weathering. The supply of ions to the ocean via rivers was consequently less. On the other hand, seafloor spreading was most probably faster with more seawater circulated through the spreading ridges. Isotope studies ($^{87}Sr/^{86}Sr$) of seawater in early Precambrian rocks indicate that at that time the composition of seawater was more strongly controlled by circulation through the basalt on the spreading ridges. We can say that the chemical composition of the ocean was buffered by material from the spreading ridge, i.e. mantle material (Veizer 1982).

3.10 Clastic Sedimentation in the Oceans

Clastic sediments are produced chiefly on the continents and are brought to ocean areas through fluvial or aeolian transport. Island arcs associated with volcanism may produce large amounts of sediment compared to their area because they are tectonically active, which leads to elevation and accelerated erosion. Volcanic rocks are for the most part basic and weather quickly, forming large quantities of sediments around volcanic island groups, while fine-grained volcanic ash becomes spread over wide areas. Submarine volcanism may also produce some sediment, for example along the Mid-Atlantic Ridge, but this is very limited.

The main supply of clastic sediment is fed into the ocean through deltas, then transported along the coast and down the continental slope to the abyssal plains. Around Antarctica there is a significant amount of deposition of clastic, glacial sediments. In areas in the middle of the Atlantic Ocean, far from land, the rate of sedimentation is as low as 1–10 mm/1,000 years. The Atlantic receives a relatively large supply of clastic sediment, in particular from seven major rivers: the St. Lawrence, Mississippi, Orinoco, Amazon, Congo, Niger and Rhine. Exceptionally high sedimentation rates characterise the Gulf of Mexico, where rapid deposition of thick sequences from the Mississippi delta has prevailed since Mesozoic times.

The South American and African continents drain mainly into the Atlantic. The water divide between the Atlantic and the Pacific Oceans lies far to the west in South America, and that with the Indian Ocean in Africa is far to the east (Fig. 7.16).

The Pacific Ocean is surrounded by a belt of volcanic regions and island arcs. There are relatively few rivers that carry large amounts of clastic sediment directly into the Pacific Ocean, in contrast to the Atlantic. Sediment which is eroded, for example on the Asian continent, is deposited in shallow marine areas (marginal seas) such as the Yellow Sea and China Sea. The sediments are cut off from further transport by the island arc running from Japan and southwards. The Pacific Ocean is therefore dominated by volcanic sediments.

Volcanic sedimentation takes the form of volcanic dust and glass, which may be transported aerially over long distances. After sedimentation, volcanic glass will turn into *palagonite*, an amorphous compound formed by hydration of basaltic tuff. Palagonite may then be further converted into montmorillonite or zeolite minerals. The zeolite phillipsite is very widely found in the Pacific, but is scarce in the other oceans. Pumice is also a volcanic product, and may drift floating over great distances. The eruption of volcanoes in the Pacific Ocean area in historic times has shown that large eruptions produce 10^9–10^{10} tonnes of ash, and much the same amount of pumice and agglomerates.

Submarine volcanism, by contrast, produces very little ash to form sediment. The lava which flows out onto the seabed will solidify as an insulating crust on

Table 3.1 Review of the ratio between mechanical and chemical denudation of the different continents (After Garrels and Machenzie 1971)

Continent	Annual chemical denudation (tonnes/km)	Annual mechanical denudation (tonnes/km)	Ratio mechanical/chemical denudation
North America	33	86	2.6
South America	28	56	2.0
Asia	32	310	9.7
Africa	24	17	0.7
Europe	42	27	0.65
Australia	2	27	10.0

contact with the water (often forming pillow lava), so that little volcanic matter goes into suspension.

Weathering and erosion processes are responsible for the entire volume of sediment which can be deposited in sedimentary basins. Material added by rivers takes the form of clastic and dissolved matter. The ratio between the quantities of these two forms of sediment addition is a function of precipitation, temperature and relief. Dry areas, like Australia, produce mainly clastic material, while the African continent produces mainly dissolved material because of the intensive weathering in some parts of the continent (Table 3.1).

Further Reading

Garrels, R.M. and Machenzie, F.T. 1971. Evolution of Sedimentary Rocks. W.W. Norton & Co Inc., New York, NY, 397 pp.

Kenneth 1982. Marine Geology. Prentice Hall. Englewood Cliffs. 813 pp.

Chamley, H. 1989. Clay Sedimentology. Springer, New York, 623 pp.

Chester, R. 1990. Marine Geochemistry. Unwin Hyman, London, 698 pp.

Eslinger, E. and Pevear, D. 1988. Clay Minerals for Petroleum Geologists and Engineers. SEPM Short Course 22.

Garrels, R.M. and Christ, C.L. 1965. Solutions, Minerals and Equilibria. Harper and Row, New York, 450 pp.

Manahan, S.E. 1993. Fundamentals of Environmental Chemistry. Lewis Publ., Chelsea, MI, 844 pp.

Saigal, G.C. and Bjørlykke, K. 1987. Carbonate cements in clastic reservoir rocks from offshore Norway – Relationships between isotopic composition, textural development and burial depth. In: Marshall, J.D. (ed.), Diagenesis of Sedimentary Sequences. Geological Society Special Publication 36, 313–324.

Veizer, J. 1982. Mantle buffering and the early Oceans. Naturvissenshaffen 69, 173–188.

Velde, B. 1995. Origin and Mineralogy of Clays. Springer, Berlin, 334 pp.

Weaver, C.E. 1989. Clays, muds and shales. Developments in Sedimentology 44, 819 pp.