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Oxygen-based redox systems in dynamic Archean oceans

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The redox texture of Archean oceans is highly debated at present mainly because it has direct bearing on when in Earth's history oxygenic photosynthesis and thus also aerobic respiration developed. Currently there are essentially three models. One depicts Archean oceans as completely anoxic based on the principle that oxygenic photosynthesis only developed in Early Paleoprotrozoic times during the GOE at 2,3-2,4 Ga. A second depicts a permanently stratified ocean with shallow oxygenated water in the photic zone overlying anoxic deep water. A third suggests the presence of local and probably transient oxygen "oases" in near shore environments of otherwise totally anoxic oceans. In all three models the anoxic water columns are considered enriched in dissolved ferrous iron to allow for deposition of BIFs through precipitation of $Fe(OH)_3$ by anaerobic iron oxidizing photoautotrophs in the anoxic situation or via reaction with free oxygen in the stratified system. In the oxygen oasis model either of the two processes could have led to deposition of BIF.

However, detailed sedimentary facies analyses strongly suggest that none of these redox models are fully applicable to Archean oceans. By far the most unlikely scenario is that of a totally anoxic ferrous ocean that predicts shallow sediments to be enriched in iron over deeper water facies due to activity of iron oxidizing photoautotrophs. However, there is no evidence for this in upward-shallowing depositional systems tracts in Archean sedimentary successions. Rather the opposite is true in that iron-rich sediments typically represents the deepest water facies with iron-depleted siliciclastics or stromatolitic carbonates developed in shallow environments; distributions that are best explained by having free oxygen available in shallower water environments in line with the stratified ocean or oxygen oasis model. The problem with these models is that depositional facies reconstructions of Archean carbonate platforms successions and deep water BIFs illustrate that in some basins the oxic-anoxic redox boundary was situated far below the agitated water column and photic zone. This implies extensive downward transport of oxygen and thus dynamic water circulation systems in Archean oceans. In turn this argues against existence of a permanently stratified ocean or preservation of local oxygen oases for any significant length of time.

Facies reconstructions in deep water microbanded BIF's require a further very significant modification to current Archean ocean models. These indicate that primary sedimentary hematite BIF commonly represents the most distal and deepest water facies and could only have been preserved if the precursor $Fe(OH)_3$ settled from a redox interface along the base of a buoyant ferrous hydrothermal plume that was detached from the ocean floor. This model requires that oxygen derived from photosynthesis in shallow water circulated down to deep water, probably via down-welling cold waters from polar regions (manifested by the presence of glacial deposits in Archean successions), creating a weakly oxygenated ocean basin system invaded by buoyant anoxic ferrous plumes. In areas where these plumes were in contact with the basin floor, magnetite and/or carbonate facies iron formation formed preferentially, the latter in areas of higher organic carbon influx. A sufficient flux of free oxygen thus appears to have been available in the oceans to create redox systems rather similar to that of to modern oceans; but at much lower concentrations as indicated for example by the absence of Ce anomalies in Archean iron formations and marine carbonates. However, there was sufficient free oxygen available in some ocean basins to form extensive manganese deposits as far back in time as at least 3,2 Ga. This revised model of a dynamic circulating ocean not only has wide implications for reconstruction of microbial communities in Archean oceans but may also help explain why the rise of oxygen in the atmosphere took place so long after development of oxygenic photosynthesis in the oceans; simply because of its consumption by reduced components in vast areas of continuously recycled ocean floor crust for example.