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Modern Black Sea oceanography applied to the end-Permian extinction event

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Abstract The modern Black Sea has a mixed upper layer in the top 150–200 m of the water column, below which the water is anoxic, separated from the mixed layer by a redox boundary. There is limited vertical movement of water. Pyrite framboids form in the water column of the anoxic zone, then have been traditionally interpreted to sink immediately and accumulate in the sediments of the Black Sea. Thus the occurrence of framboids in sediments in the rock record is widely interpreted to indicate poorly oxygenated to anoxic conditions in ancient environments. However, in the Permian–Triassic boundary (PTB) microbialites of South China, which formed in shallow marine conditions in contact with the atmosphere, the published occurrence of framboids is inconsistent with abundant gastropod and ostracod shells in the microbialite. Furthermore, in the modern Black Sea, (a) framboids may be suspended, attached to organic matter in the water column, thus not settle to the sea floor immediately after formation; and (b) the redox zone is an unstable complex area subject to rapid vertical water movement including occasional upwelling. The model presented here supposes that upwelling through the redox zone can lead to upward transport of suspended pyrite framboids into the mixed layer. Advective circulation could then draw suspended framboids onto the shelf to be deposited in oxygenated sediments. In the Permian–Triassic transition, if framboids were upwelled from below the redox boundary and mixed with oxygenated waters, sediment deposited in these conditions could provide a mixed signal for potentially misleading interpretations of low oxygen conditions. However, stratigraphic sampling resolution of post-extinction microbialites is currently insufficient to demonstrate possible separation of framboid-bearing layers from those where framboids are absent.

Profound differences between microbialite constructors and sequences between the western and eastern Tethys demonstrate barriers to migration of microbial organisms. However, framboid occurrences in both areas indicate upwelling and emphasize vertical movement of water from the lower to upper ocean, yet the mixed layer advective motion may not have been as effective as in modern oceans. In the modern Black Sea, such advection is highly effective in water mixing, and provides an interesting contrast with the PTB times.

Key words mass extinction, Permian–Triassic boundary, microbialite, ostracods, gastropods, anoxia, Black Sea

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1 Introduction and aims

Causes of the end-Permian mass extinction remain problematic, but a growing body of evidence points to low oxygen levels throughout much of the ocean system. A range of measures of low oxygen includes pyrite framboids (Bond and Wignall, 2010; Tian *et al*., 2014), sulphur isotopes (Paytan *et al*., 2011), redox-sensitive elements (*e.g.*, Algeo *et al.*, 2010) and biomarkers (*e.g.*, Luo *et al*., 2013). Much work focuses on open shelf settings, and is establishing an interpretation of reduced oxygen in the deeper shelf and the deeper open ocean. However, there remains an issue of interpretation of oxygenation in locations where physical bio-sedimentary and shelly fossil evidence point to normal levels of oxygenation. For example, at Meishan, the GSSP (Global stratotype section and point) for the Permian−Triassic boundary, the open shelf sediments there contain abundant trace fossils, including open tunnels indicative of excavating organisms that must have needed oxygen. Danovaro *et al.* (2010) showed that modern metazoans can exist in low oxygen settings; these are very small metazoans in the Mediterranean Sea. Gingras *et al.* (2011) demonstrated that small metazoans can live in oxygenated microenvironments, receiving oxygen from photosynthesizing microbial organisms in otherwise low oxygen settings. These observations were explored by Forel *et al.* (2013) for the Permian−Triassic boundary (PTB) microbialites. However, those interpretations can apply only to situations where the amount of oxygen produced locally can be matched to the sedimentary evidence of shelly remains in the sediments. If there are abundant shelly remains, as in the case of many PTB microbialites, then local oxygen production within the microbialite may not have been sufficient to reasonably explain presence of abundant shelly fossils. There is also the issue, in the fossil record, of demonstrating whether or not the shelly remains were alive at the same time as the photosynthesizing oxygen-producing microbia. In the geological record, the issue of time-averaging in sediments is an important barrier to proving co-existence of organisms.

This paper addresses the issue of whether the microbialite system, that developed immediately after the end-Permian extinction event, grew in oxygenated conditions or not, using information from oceanographic processes in the modern Black Sea. The issue arises because of the discovery of pyrite framboids in the microbialite in one site (Laolongdong, Chongqing, South China; see Liao *et al.*, 2010). In general, the PTB microbialites are rich in shelly remains of ostracods and gastropods that may be reasonably viewed as requiring fully oxygenated conditions in which to grow. Therefore there is a seeming contradiction between the presence of pyrite framboids indicating low oxygen, on one hand, and shelly faunas in shallow marine waters indicating normal oxygen, on the other hand. Kershaw *et al.* (2012) suggested that this contradiction could be explained by oxygen-poor water upwelling and choking the continental shelves. However, the current paper investigates this problem in relation to modern oceanographic processes in the Black Sea and provides an alternative potential explanation.

2 Black Sea oceanography

2.1 General pattern

There is a huge literature database on the Black Sea, because of its peculiar setting in the global aquatic system, being the only large water body currently existing that is largely anoxic. Critical to the current paper, the nature of the shallow Black Sea circulation is of great interest.

The Black Sea is divided into two basins, east and west, by a north−south orientated seafloor topographic ridge in its centre. However, water circulation consists of two forms of wind-driven water circulaton that influences both the upper (mixed) layer of oxygenated water, and the upper portion of the underlying anoxic water. Firstly, the surface waters are driven by westward-moving winds from the Caucasus Mountains in the northeast, to produce a cyclonic (anticlockwise) rim current along the continental slope (Figure 1), that varies from weak to strong, and completes one loop around the Black Sea in only a few months (Zatsepin *et al*., 2007). Secondly, two major anticyclonic gyres exist as permanent features, one in the east and one in the west basin (Figure 1). Also, anticyclonic mesoscale eddies and minor eddies develop across the Black Sea and are unstable, showing large changes over periods of only 3−6 months (Zatsepin *et al.*, 2007; Tulzhikin, 2008).

Thus, due to eddy flows, the upper 150−200 m of the Black Sea water mass is mixed by surface circulation and is aerated in contact with the atmosphere (Figure 2). Oxygen levels decline downwards, reaching zero at the redox boundary (Ostrovskii and Zatsepin, 2011) that lies