High resolution sediment microfabric and geochemical analysis reveals seasonal scale redox mineralisation, anthropogenic environmental change and pollution in England’s largest natural lake - Windermere

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Many lakes in industrialised areas have undergone anthropogenically driven eutrophication and increases in pollution leading to decreased water and sediment quality. In some cases, these effects are enhanced by seasonally changing lake redox conditions that may act to concentrate potentially toxic elements sufficiently to exceed internationally recognised Sediment Quality Standards, impacting key species and jeopardizing water supply. A combined, geochemical and sediment microfabric analysis is applied to reconstruct the history of cultural eutrophication and pollution in the North and South Basins of Windermere, England’s largest natural lake. We also document a record of seismicity and link increasing sedimentation rates and sediment instability. The onset and development of eutrophication in Windermere occurred from the mid-19th to the early 20th centuries. Raised lake productivity is indicated by an increase in sedimentary $\delta^{13}$C, and increased pollution by elevated sedimentary trace metals (Pb, Zn, Cu, Hg, and As), likely enhanced by incorporation and adsorption to settling diatom aggregates, preserved as sedimentary laminae. In the South Basin of the lake, contemporaneous increasing sediment $\delta^{15}$N values also occur in step with increasing Zn, Hg, Cu from this time, linking metal enrichment to the input of isotopically heavy nitrate (N) from anthropogenic sources including sewage. From around 1930, a decrease in Mn and Fe-rich laminae indicate reduced deep water ventilation, and increased incidence of sediment anoxia, being most intense in the deeper North Basin where benthic activity intermittently ceased. Strongly reducing conditions in the sediment promoted Fe and Mn reduction and the formation of unusual Pb-bearing barite, hitherto only described from toxic mine wastes and contaminated soils. In the North Basin cores a clay rich laminae dated 1979-1980 is shown to be a mass transport deposit linked to large scale slope failure likely caused by the 4.7 ML 1979 Carlisle earthquake. Slope failure was exacerbated by preconditioning principally by increased sedimentation as a result of anthropogenic activities. From 1980 there was a recovery in oxygenation with Mn and Fe rich laminae returning in some parts. But in the South Basin, the continued impacts of sewage discharge is indicated by elevated $\delta^{15}$N of organic matter. Imaging and X-ray microanalysis using scanning electron microscopy has enabled the identification of seasonal-scale redox mineralisation of Mn, Fe and Ba related to intermittent sediment anoxia. Elevated concentrations of Mn, Fe, Ba, and As also occur in the surficial sediment.
and provide evidence for dynamic redox mobilisation of potentially toxic elements that may be released to the lake waters. Concentrations of As, in particular, exceed international Sediment Quality Standards. These surface enrichments in As and other toxic elements may become more prevalent in the future with climate change driving lengthened summer stratification in the lake.