# Trace mineral mapping is key to recognizing black shales as dynamic marine systems

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Fine grained shale sediments in lake and continental margin settings provide one of the most continuous and highest temporal resolution palaeoenvironmental records available in the sedimentary record. Suspension deposits provide an integrated record of continental process via detrital mineralogy as well as water column composition through biogenic minerals, authigenic precipitates and synsedimentary formation of cements and crusts. The challenge with laminated sediments has been the sub micrometer scale of the mineral grains as well as the mm alternation of composition between laminae. Technological inability to both image and quantify changes within these laminae have resulted in bulk chemical analysis leading to the sense that these sediments are homogenous.

Here we apply a new SEM-based, sub-µm resolution mineral mapping system (Nanomin) to determine trace mineral variation across mm laminae of black shale deposits of the Permian Stuart Range Formation of South Australia. Currently the most advanced SEM-based mineral mapping system, Nanomin quantitatively resolves multiple minerals within the excitation volume of every single pixel allowing for multiple phase determinations. Laminae to laminae variability show an oscillation between laminae dominated by framboidal pyrite and labile organic matter and organic poor laminae featuring abundant manganese carbonate (kutnohorite) forming cyclical deposits interpreted as varves. These couplets identify the cyclical oscillation of water column redox conditions with pyrite deposition indicating stratification and euxinic conditions in an ancient fjord. Freshening across a sill resulted in precipitation of dissolved Mn as Mn oxide, subsequently preserved as kuthnohorite.

Alternative approaches including bulk XRD or elemental analyses cannot identify the significance of the spatial distribution in alternate laminae of the kuthnohorite and framboidal pyrite, leading to past interpretations of the succession as a prolonged period of continuous anoxic conditions rather than the dynamic system evident from the high spatial resolution data. Indeed, the new perspective offered by this technology shows greater variability between adjacent laminae (i.e. centennial to decadal time scales) than is evident in the average composition of the bulk rock samples across the entirety of the shale interval.