

## ***Interactive comment on “Eastern Mediterranean Sea circulation inferred from the conditions of S1 sapropel deposition” by K. Tachikawa et al.***

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Answer to comments by reviewer #1 At first we would like to thank reviewer #1 for the detailed comments. Below we answer to five points evoked by the reviewer point by point. To further support our argument and avoid possible misunderstanding, we will add some new information including benthic foraminiferal micropaleontological data in our revised version.

1/ The justification for the use of certain geochemical ratio needs to be stronger. Here the reviewer pointed out that Br/Cl and S/Cl variability could be biased due to Cl normalization because Cl is tightly related to porosity. We agree that Cl is an excellent indicator of porosity of marine sediment cores. Since some part of Br and S XRF signal could be related to porosity, we used Cl normalized XRF intensity ratios. Below, we

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compare XRF intensity of Br (S) with Br/Cl (S/Cl) intensity ratio. It is clear that the raw XRF intensity and the corresponding Cl normalized ratio present very similar variability (Fig. 1). This is because the variability of Br and S intensities of core MD04-2722 at the studied interval is essentially determined by organic matter and sulphide mineral contents, respectively, as we stated in the manuscript. We thus consider that the normalization does not introduce any noticeable bias to the results of core MD04-2722. Indeed, Br/Cl intensity ratio is successfully used in our recent paper (Cartapanis et al., 2014). In the revised manuscript, we will state that raw XRF intensity and corresponding Cl normalized ratio present close variability to avoid potential confusion. Then, reviewer #1 mentioned that “through the manuscript, Author’s use different geochemical ratios but I really miss a principal component analysis only for elements (no for the element/Al ratio)”. We suppose that the reviewer referred the ICP-MS data including trace elements that are impossible to be determined by XRF scanning. It is worth noting that raw XRF intensity is influenced by matrix effect due to marked change of sediment nature (organic-rich S1 interval), which may introduce artefact to principal component analysis (PCA). To answer to the reviewer’s comment, PCA is performed for concentration of elements that were measured for the whole studied period (Al, K, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Mo, Sb and Ba). The result indicates that 75% of the total variance could be expressed by three principal components. The first component explains 53% of data set variance with high loadings for Fe (0.38), Ni (0.43) and Cu (0.39), which corresponds to the variability of elements associated with downward sulphidisation. The second component explains 23% of variance with high loadings for Ti (0.51), K (0.42) and Ca (-0.36) demonstrating dilution between detrital and carbonate fractions. The result confirms that the major elemental changes are associated with the downward sulphidisation, and the mutual dilution between detrital fractions and CaCO<sub>3</sub>. Since the PCA does not bring additional useful information, we will not integrate this result in the revised version.

2/ Justification of U/Al and Mo/Al along the interval affected by downward sulphidisation. The criticised point here is that downward sulphidisation may affect U and Mo, so

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the enrichment of these elements before S1 deposition due to reduced oxygenation is dubious. We agree that the remobilization of U and Mo would not be totally ignored (Martinez-Ruiz et al., 2015). Since PCA result indicates that Cu and Ni are affected by the sulphidation, we compare U and Mo of core MD05-2722 with these elements. Depth-profiles of U and Mo are clearly different from those of Cu and Ni with maximum values at shallower depths in core (Fig. 2). Furthermore, reduced oxygenation condition prior to S1 deposition is also supported by the appearance of benthic foraminiferal species that is a marker of low oxygenation condition (*Globobulimina* spp.) at 138 cm (12.2 cal ka B.P.) and a decreasing tendency of total benthic foraminifera at 142 cm (12.6 cal ka B.P.). Two major factors affecting benthic foraminiferal assemblage are food supply and water oxygenation (Jorissen et al., 1995). Since the Ba/Al change indicated increasing trend of export production just before the S1 deposition (Figure 2 in our CPD manuscript), it is logical to assume that the observed reduction of benthic foraminiferal number was related to oxygen depletion. The consistent result based on both geochemistry and micropaleontology suggests that the influence of downward sulphidation on Mo and U distribution is minor and the accumulation of these trace elements were essentially produced by reduced oxygenation in bottom/pore waters. We will add the information based on benthic foraminiferal result in the revised version.

3/ Justification of *G. ruber*  $\delta^{18}\text{O}$  as fresh water proxy. The reviewer noticed that variability of *G. ruber*  $\delta^{18}\text{O}$  and of the calculated seawater  $\delta^{18}\text{O}$  anomaly of core MD04-2722 is very similar, thus it might simply indicate the changes in global ice volume. Similar *G. ruber*  $\delta^{18}\text{O}$  and the seawater  $\delta^{18}\text{O}$  anomaly changes are explained by a small temperature effect. Below we compare seawater  $\delta^{18}\text{O}$  anomaly of core MD04-2722 with global oceanic  $\delta^{18}\text{O}$  change (Waelbroeck et al., 2002) using a presentation shown in Rogerson et al. (2004) as suggested by reviewer. We select this global sea level estimate since it was successfully used to evaluate Adriatic Sea hydrology during Holocene (Siani et al., 2013). The ice volume effect cannot explain the observed large amplitude of  $\delta^{18}\text{O}$  anomaly of 2.7‰ from 20 ka to 9.6 ka for core MD04-2722 since  $\delta^{18}\text{O}$  change related to continental ice volume accounts only for 0.83‰ for the same

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span (Fig. 3). Further, the period of the strong depletion of seawater  $\delta^{18}\text{O}$  obtained for core MD04-2722 (12.5 to 5.5 ka) corresponds to AHP that is consistent with our hypothesis of surface water freshening. Consequently, we will not re-write Chapter “6.2 Conditions of bottom water circulation prior to S1 deposition”. In the revised version, we will clearly state the large amplitude of the seawater  $\delta^{18}\text{O}$  anomaly of core MD04-2722 that cannot be explained solely by the change in global seawater  $\delta^{18}\text{O}$  due to the deglaciation.

4/ Multiple re-ventilation in the middle of the S1 period. The subject here is whether the S1 interruption was a single event or constituted by multiple events, and whether forcings were enough strong to induce re-ventilation. We agree with the reviewer that our results do not provide direct evidence for multiple events. The possibility of multiple events is based on previous geochemical and micropaleontological studies (Rohling et al., 2015 and references therein) and the modelling experiments showing difficulty to maintain sapropel deposition for several thousand years (Grimm, 2012). We are aware that the spikes of oxygenation index could be formed by bioturbation. However, multiple events cannot be totally discarded because the stability of stagnant circulation mode, oxygen consumption during circulation, and the size of forcing necessary to re-ventilation at a given state are still poorly constrained. In our knowledge, the only simulation of S1 interruption was based on physics-only model and showed that 2-3°C cooling is enough to ventilate upper 1,250 m in the Eastern Mediterranean Sea (Myers and Rohling, 2000). No simulation was performed by changing both temperature and salinity. We will carefully revise this part and change the label of circulation sketch in Figure 6 from “9-8 ka” to “S1 interruption” to clarify our message.

5/ Difference between total ventilation recovery at the S1 termination and previous S1 interruption. The reviewer asked difference of oxygenation mechanism between S1 interruption and S1 termination. Considering the present-day subtle density difference between the present Levantine intermediate water (LIW) and Eastern Mediterranean Deep Water (EMDW) (section 2), there is not enough evidence to determine whether

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the LIW ventilation started prior to the EMDW formation or distinct circulation mode existed. Instead, we speculate that background conditions might be quite different between the S1 interruption and S1 termination: General reduction of fresh water inputs to the Mediterranean Sea is expected at S1 termination as illustrated by insolation changes (Figure 4). Moreover during S1 interruption, saline glacial water could be partially mixed with fresher water masses, leading to attenuation of vertical salinity gradient. This might facilitate total recovery of basin-wide ventilation. We will add some explanation in the revised manuscript about possible processes but more data on water mass tracers and modelling studies will be required for more precise discussion.

Besides, the reviewer asked to modify figures because “Fig. 4 and Fig. 5 is confuse or include depth and age in X-axis at least one figure will be helpful”. To avoid that the figures are too busy, we indicate several key periods with coloured bands that are common for depth profiles and age profiles. With Table 1 presenting depth-age correspondence, we believe that there is no confusion in Figures 4 and 5.

Finally, the reviewer commented that “Also is rare that U, V, Mo (u/um) content is virtually the same that these element/Al ratio. Is also rare obtain major elements (Al, Fe, Mn, etc) by ICP-MS.” The similar variability between trace element concentration and corresponding element/Al ratio indicates that the variability is principally determined by authigenic enrichment. This is commonly observed in environments of oxygen-depleted conditions such as oxygen minimum zones. We used ICP-MS to measure maximal number of elements at the same time. As shown in the original manuscript, all the results are controlled by analysis of Geostandards that confirmed the quality of our data.

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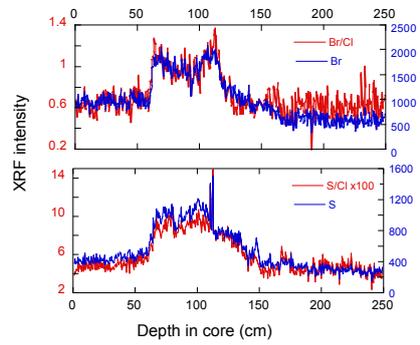


Fig. 1. Comparison between XRF intensity and intensity ratio of core MD04-2722.

Fig. 1.

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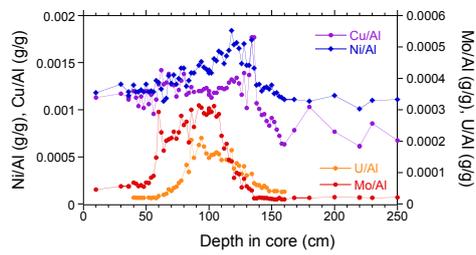


Fig. 2. Cu/Al, Ni/Al, U/Al and Mo/Al of core MD04-2722

Fig. 2.

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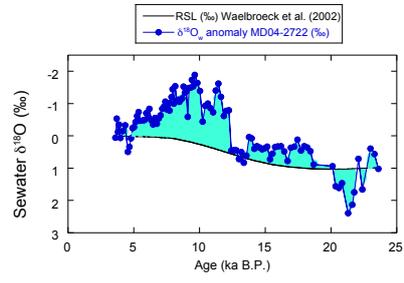


Fig. 3. Comparison between surface water  $\delta^{18}\text{O}$  for core MD04-2722 and global seawater  $\delta^{18}\text{O}$  change

Fig. 3.