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## 1. Introduction

An international and multidisciplinary group of scientists have recently joined efforts to organize the challenging endeavor of drilling through the thick Messinian evaporites found in deep Mediterranean basins (IODP pre-Proposal P857B DREAM; Camerlenghi et al., 2014; Lofi and Camerlenghi, 2014). The targeted deep basin evaporites reach up to 3 km in thickness (Hsü, 1973) and are thought to have resulted from restricted connectivity of the Mediterranean Basin to the Atlantic Ocean that lead to the Messinian Salinity Crisis (MSC). It has been suggested that deposition of the MSC salt giant has greatly affected the global oceans by sequestering 5% (Ryan, 1973; 2008) to 10% (Garcia-Castellanos and Villaseñor, 2011) of their salt content into the Mediterranean. Also, by contributing warm, saline water to northern latitudes, the MSC influenced Atlantic Meridional Overturning Circulation and, consequently, global climatic shifts (Hernández-Molina et al., 2014). Among the major stratigraphically-driven findings of modern geoscience, the MSC stands alone as being supported by an 'outrageously under-sampled stratigraphic record' (CIESM, 2008). For several decades, focused investigation of the MSC within various interdisciplinary studies was aimed at understanding the mechanisms governing its timing, paleogeography, and the inter-relationship between external forcing and physical systems response. However, while the deep-basin halite was penetrated in its uppermost part (Fig. 1), the prohibitive risk and high drilling cost of ~~drilling-recovering~~ cores through the entire deep-basin MSC unit has resulted in a critical lack of data. Scientific drilling of the deep Mediterranean basins has been repeatedly called for in order to test and validate different hypotheses regarding the MSC in the deep Mediterranean basins (CIESM, 2008; Dela Pierre et al., 2014; Gvirtzman et al., 2017; Manzi et al., 2015, 2018; Meilijson et al., 2018), but has yet to be achieved.

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59 24 The MSC came into awareness and was documented as early as the 1950's, when massive  
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61 25 evaporite outcrops in the peri-Mediterranean were identified as co-occurring around the end of  
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63 26 the Miocene (Selli, 1954; Ogniben, 1957). However, the MSC magnitude and extent became  
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65 27 clear only when seismic imaging penetrated the massive diapiric and stratified salt bodies of the  
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67 28 Mediterranean Sea, reaching more than 2 km in thickness and stretching across vast parts of the  
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69 29 basin (e.g., Bourcart et al., 1958; Alinat and Cousteau, 1962; Cornet, 1968; Ryan et al., 1971;  
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71 30 Bellaiche et al. 1974; Ryan, 1976). One of the oldest controversies related to the MSC concerns  
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73 31 the magnitude and timing of sea-level lowering and desiccation, where several models for  
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75 32 evaporite formation have been suggested. Some have proposed that salt was precipitated in deep  
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77 33 basins under a deep-water environment (Schmalz, 1969; Debenedetti, 1982; Sonnenfeld and  
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79 34 Finetti, 2011), while other scenarios promoted a desiccated shallow-water environment (Hsu,  
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81 35 1973). A hybrid model was proposed, with early brine formation in the deep Mediterranean,  
82  
83 36 preceding substantial drawdown, followed by massive salt precipitation during gateway closure  
84  
85 37 (Ryan, 2008; Garcia-Castellanos and Villaseñor, 2011; Lofi et al., 2011). Clauzon et al. (1996)  
86  
87 38 recognized the occurrence of shallow-water first cycle gypsum beds of the same age in many  
88  
89 39 localities in the western and eastern Mediterranean. Based on this observation they presented a 2-  
90  
91 40 step model, in which the surface of the Mediterranean Sea remained close to the global oceans  
92  
93 41 level during the early part of the crisis, and deep-basin evaporites formed following sea-level  
94  
95 42 drop of the subsequent step. Based on this model, Ryan (2011) described the geodynamic  
96  
97 43 response of the basin to each of these steps: 1) Significant deepening of the basins by isostatic  
98  
99 44 load due to an increase in weight of the brine layer. 2) As the basins dried out, the loss of weight  
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101 45 of the water led to regional isostatic uplift that permanently closed the prior inlets.  
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115 46 Van Couvering et al. (1976) were the first to propose a similar 2-step model, which also  
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117 47 portrays an early deposition of halite in the deep basins: (1) An initial deep-water phase marked  
118  
119 48 by refluxive concentration of brines and controlled by a tectonically elevated sill, during which  
120  
121 49 evaporites and associated sediments accumulated simultaneously near the surface in marginal  
122  
123 50 areas (gypsum) and within great saline water bodies in the depths of the basin (halite). (2) A  
124  
125 51 terminal phase of total isolation, caused by an eustatic sea-level drop, during which erosion and  
126  
127 52 desiccation features were developed that fit the "deep-basin, shallow-water" model. However,  
128  
129 53 this model was later abandoned in favor of what developed into the CIESM (2008) workshop  
130  
131 54 consensus stratigraphic model, which was elaborated in the extensive review of the MSC by  
132  
133 55 Roveri et al. (2014a) and widely cited.

136  
137 56 The CIESM (2008) stratigraphic model of the MSC is based on correlation of Mediterranean  
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139 57 evaporite sequences deposited in marginal to intermediate basins, and their isotopic signatures  
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141 58 (Keogh and Butler, 1999; Müller and Mueller, 1991; Flecker and Ellam, 2006). While the  
142  
143 59 division of MSC units differs slightly in terminology between the CIESM (2008) model and the  
144  
145 60 widely used review of the MSC presented by Roveri et al. (2014a), they both stem from the same  
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147 61 stratigraphic concepts, and are jointly referred to here as the 'consensus model' for MSC  
148  
149 62 chronology. These studies demonstrate that partial connectivity with the Atlantic Ocean persisted  
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151 63 throughout the first phase of gypsum deposition, lasting for ~370 kyr and known as MSC phase  
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153 64 1: Primary Lower Gypsum [PLG], 5.97–5.6 Ma.

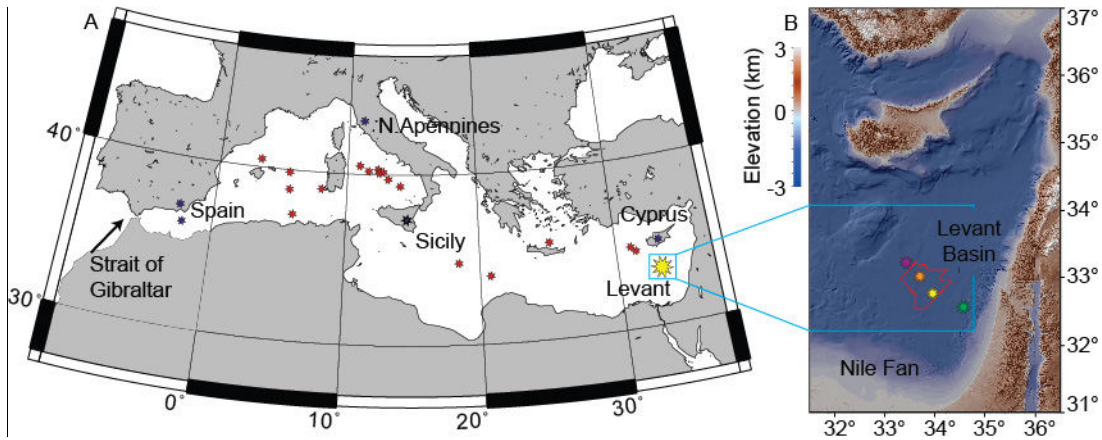


Figure 1. Map of the Mediterranean Sea marking the study area and referenced sections.

A. Map of Mediterranean Sea marking study area (yellow star); main referenced sections (blue stars); and Deep Sea Drilling Project and Ocean Drilling Program wells (red stars), which penetrated MSC halite deposits only at their uppermost part. B. Bathymetry A shaded relief map of the Levant Basin and surrounding area (Hall et al., 1994, 2015). Red polygon outlines the three-dimensional seismic cube referred to in this study. Well locations marked by stars: Aphrodite-1 (purple star), Leviathan-1 (orange), Dolphin (yellow), and Sara (Green).

During the PLG, euxinic shales and dolostones were thought to have been deposited in the deep basins in parallel to gypsum deposition in the proximal settings (Lange and Krijgsman, 2010). However, using sonic and resistivity logs and samples from cuttings of the 497-Muchamiel oil-industry well, Ochoa et al. (2015) found-observed all 14 of the known first-stage gypsum beds present in the Sorbas Basin, offshore southeast Spain, deep (875 -965 m) below the present-day sea level. This finding-observation was interpreted-to-contradict-regarded opposite to previous assumptions that only shales would be present in this interval of the deep basins (CIESM, 2008; Roveri et al., 2014a).

The thick salt unit was interpreted as being accumulated during the succeeding MSC acme, a short period of ~50 kyr known as MSC phase 2: Resedimented Lower Gypsum [RLG], 5.6–5.55 Ma (although its top is often marked at 5.53 Ma in different cyclostratigraphic schemes (e.g.,

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85 Roveri et al., 2014a; Manzi et al., 2015) due to the ‘Messinian gap’, during which Messinian  
86 erosion and/or deposition of resedimented gypsum and halite occurred). A model depicting the  
87 desiccation of the Mediterranean during stage 2 was proposed to explain its formation over such  
88 a short period of time. This model entails a massive sea-level drawdown and consequent  
89 removal and re-deposition of the PLG gypsum, and a seasonal or long-term deposition of halite  
90 in intermediate to deep-water basins. Lastly, the third phase of the MSC was defined within the  
91 Upper Evaporites or Gypsum sequences (UG), which include clastic or brackish sediments  
92 culminating in the Lago-Mare deposits (5.55-5.33 Ma). The latter consists of several units with  
93 7-10 sedimentary cycles identified in the Upper Gypsum of Italy overlying erosional surfaces  
94 and angular unconformities, and underlying Pliocene sediments (Hilgen et al., 2007; Krijgsman  
95 et al., 2010; Roveri et al., 2014a). A recent review of different Lago-Mare deposits depicts that  
96 three main pulses of seaward-transport occurred within the time-interval 5.7064-5.3033 Ma, and  
97 suggests abandonment of previous concepts dealing with a unique chronostratigraphic unit,  
98 favoring several episodes of flooding (Couto et al., 2014). Nonetheless, the first influx of  
99 Paratethyan organisms, identified through the dinoflagellate cyst record near Malaga within a fan  
100 delta, was found overlying the intra-Messinian truncation surface (IMTS) (Couto et al., 2014).

101 Recent industrial activities targeting hydrocarbon reservoirs in the Eastern Mediterranean  
102 basin-Basin provide the scientific community with unparalleled seismic~~s~~, well logs, and cuttings  
103 across the salt interval. The current work takes advantage of these industrial data to address two  
104 critical issues regarding Messinian stratigraphy in the deep Eastern Mediterranean Basin, which  
105 impact our basic understanding of this event: (1) To evaluate the composition, age and duration  
106 of evaporite deposition in the Eastern Mediterranean. (2) To characterize, interpret, and  
107 stratigraphically position the sediments overlying the IMTS (as in Gvirtzman et al., 2017),

281  
282  
283 108 termed here the Interbedded and Argillaceous Evaporites. Here, we report previously unknown  
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285 109 features and lithology of the deep basin MSC<sub>7</sub> and<sub>2</sub> by using a multi-disciplinary approach, we  
286  
287 110 provide further interpretation of their stratigraphic ~~significance~~.

## 289 290 111 **2. MSC deposits in the Levant**

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292 112 Feng et al. (2016) analyzed jointly well-log measurements and a pervasive seismic dataset,  
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294 113 and demonstrated that the seismically transparent layers composing the majority of the  
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296 114 Messinian evaporites ~~sequence deposits~~ across the deep Levant Basin ~~is-are~~ composed of pure  
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298 115 halite. The reflective layers appearing within the halite (Figs- 2, 3) were interpreted as bundles of  
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300 116 thin clay layers interbedded in the halite background, having a cumulative thickness of 25--40  
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302 117 m. Feng et al. (2016) also reported high--amplitude fan structures on the deepest internal  
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304 118 reflectors<sub>2</sub> which may suggest transport mechanisms. Later, Gvirtzman et al. (2017) argued  
305  
306 119 against a complete desiccation of the Eastern Mediterranean<sub>2</sub> following the seismic identification  
307  
308 120 of the IMTS at ~100 m below the Messinian-Zanclean boundary in the Levant Basin. Based  
309  
310 121 ~~solely~~ on interpretation of well logs ~~and correlation to shallower-water wells~~, Gvirtzman et al.  
311  
312 122 (2017) suggested that the post-truncation Messinian unit is different from the underlying salt  
313  
314 123 deposits and mostly consists of shale, sand and anhydrite. Lastly, two separate studies (Manzi et  
315  
316 124 al., 2018; Meilijson et al., 2018) have investigated the sediments underlying the evaporites, based  
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318 125 on data from different wells within the Levant Basin. Both studies address the stratigraphy of the  
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320 126 Pre-Evaporites and are aimed at providing an indication for the age of the base of the halite in the  
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322 127 deep Eastern Mediterranean, represented on seismic data in the region as the 'N' reflection  
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324 128 (Ryan, 1978; Bertoni and Cartwright, 2007). Establishing the age and duration of the deep-basin  
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326 129 halite is perhaps the most enigmatic aspect of MSC research. Both recent studies test the CIESM  
327  
328 130 stratigraphic model of the MSC (CIESM, 2008; Dela Pierre et al., 2014; Roveri et al., 2014a).

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339 131 Manzi et al. (2018) and Meilijson et al. (2018) report several similar findings, such as the  
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341 132 seismic interpretations regarding the conformity of the base of the evaporites, and thus refuting  
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343 133 the occurrence of a long hiatus at the base of the evaporites. In addition, both studies indicate  
344  
345 134 little deformation of the Levant ~~pre~~Pre-~~e~~Evaporite interval and a continuous record of the ~~upper~~  
346  
347 135 Tortonian to ~~Lower~~Messinian ~~interval~~sediments. Still, different observations reported in these  
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349 136 studies have led to continued uncertainty concerning the age and duration of salt deposition.  
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351  
352 137 Meilijson et al. (2018) considered two alternatives for the age of the base evaporites in the  
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354 138 deep basins: (1) during stage 1 (PLG) of the MSC at around 5.9 Ma, or (2) at around 5.6 Ma  
355  
356 139 during stage 2 (RLG) of the MSC, as is described in the CIESM stratigraphic model (CIESM,  
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358 140 2008; Roveri et al., 2014a). The latter would imply a major hiatus of ~370 kyr (missing the PLG  
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360 141 equivalent unit) at the base of the salt, or alternatively that the PLG is expressed as a very thin  
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362 142 interval in the uppermost Pre-Evaporites unit. A hiatus in the deep basin has not been identified,  
363  
364 143 but rather a visible lateral continuity of seismic reflectors below and at the boundary itself  
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366 144 (Meilijson et al., 2018). This finding is consistent with published regional seismic sections (Feng  
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368 145 et al., 2016; Manzi et al., 2018; Roberts and Peace, 2007) and elsewhere in the deep domain of  
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370 146 the Mediterranean (Lofi et al., 2011). Thus, Meilijson et al. (2018) concluded that the studied  
371  
372 147 section is in fact conformal and halite began to precipitate around the onset of the PLG in the  
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374 148 marginal basins, predating the CIESM consensus for halite deposition by ~300 kyr.  
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377  
378 149 Manzi et al. (2018) reported that in the Aphrodite-2 well (Fig. 1), which is the deepest  
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380 150 location along their four-well cross-section, a complete absence of foraminifera occurs from  
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382 151 3959 m upwards, 28 m below the first occurrence of anhydrite, and 33 m from the base of halite  
383  
384 152 deposition. They interpret this foraminifera barren interval (FB~~I~~I) as corresponding to the Non-  
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386 153 Distinctive Zone (NDZ) marking the onset of the MSC (5.971 Ma) in marginal settings (Gennari et  
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395 154 al., 2013; Manzi et al., 2013). Manzi et al. (2018) proposed that this interval represents the deep basin  
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397 155 expression of the PLG, followed by halite deposition during stage 2 of the MSC at around 5.6 Ma.  
398  
399 156 This FBI is argued by them to be further substantiated by a prominent peak of *Sphenolitus abies* at  
400  
401 157 3961 m, closely followed by a decrease in the number of species of calcareous nannofossils. The  
402  
403 158 FBI was also identified by Manzi et al. (2018) in the Myra well, which is situated in a more proximal  
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405 159 position, 90 km SW to the Aphrodite well. ~~Further~~ Farther landward to the west, the FBI is no longer  
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407 160 recognized in the Sara well, where the Aphrodite well equivalence of about 60 m underlying the base  
408  
409 161 of the evaporites is missing. This observation indicates that the Dolphin well should also include an  
410  
411 162 equivalent FBI, as it is positioned between the Myra well, and closer to the latter (Fig. 1). However,  
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413 163 such an FBI is not present in the Dolphin well, in which the samples include a relatively open-  
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415 164 marine foraminiferal assemblage up to the uppermost sample available for analysis, representing the  
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417 165 interval 0-9 m below the base of the evaporites (Meilijson et al., 2018). Thus, the MSC timing and  
418  
419 166 events are still debated after more than 50 years of research and over 10,000 publications.

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421  
422 167 -In recent years, different studies have been leaning towards new and very different ideas  
423  
424 168 regarding MSC chronology, and thus the mechanisms controlling the deposition of salt giants in deep  
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426 169 sea basins. Ochoa et al. (2015) demonstrated synchronous deposition of evaporites in marginal and  
427  
428 170 intermediate basins. Simon and Meijer (2017) modeled stratification in the Mediterranean during the  
429  
430 171 MSC and raised the possibility of a much earlier onset of halite in the deep basins. Finally, García-  
431  
432 172 Veigas et al. (2018) even went so far as to draw a model for an early onset of halite, yet added a  
433  
434 173 question mark next to this assumption due to lack of proof for this claim (their ~~Fig~~ fig. 12). Here, we  
435  
436 174 address this debate on the chronology of MSC events in the Mediterranean by examining the  
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438 175 recovery of deep-~~basin~~ evaporites from the Levant Basin for stratigraphic indicators that can  
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440 176 promote a better understanding of MSC chronology.  
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451 177 The MSC (CIESM, 2008; Roveri et al., 2014a) is expressed in the southeastern Levant Basin  
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453 178 margins as a thick evaporitic sequence (locally named the Mavqiim Formation), as well as clastic  
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455 179 evaporite deposits along local topographical lows (Buchbinder and Zilberman, 1997; Druckman  
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457 180 et al., 1995; Lugli et al., 2013). The MSC deposits in the deep Levant Basin have been identified  
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459 181 through seismic data, and interpreted as mainly consisting of halite, reaching a thicknesses of  
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461 182 ~2 km in the central part of the basin and pinching out upslope towards its southeastern margin  
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463 183 (Bertoni and Cartwright, 2007, 2006; Feng et al., 2016; Gardosh et al., 2008; Netzeband et al.,  
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465 184 2006; Steinberg et al., 2011). The halite sequence base and top are generally imaged as  
466  
467 185 pronounced high-amplitude seismic reflections, known as the N and M reflectors, respectively  
468  
469 186 (Ryan, 1978). Up-dip, the evaporitic sequence thins below the seismic resolution and is entirely  
470  
471 187 represented by the M ~~reflection-reflector~~ (e.g., Steinberg et al., 2010). The nomenclature of the  
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473 188 MSC section in the Levant Basin is currently based on the regional identification of a number of  
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475 189 key markers within seismic sections across the basin, with several divisions presented by  
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477 190 different studies: division of the section into 6 or 7 units (Gvirtzman et al., 2013b, 2017; Lugli et  
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479 191 al., 2013), or into ME 1-4 (Messinian evaporites), and MC 1 and 2 (Messinian clastics; Feng et  
480  
481 192 al., 2016). In this manuscript we refer to the unit numbers (Gvirtzman et al., 2017, 2013b) and  
482  
483 193 ME/MC units (Feng et al., 2016), corresponding seismically to the lithostratigraphic descriptions  
484  
485 194 and division of the Dolphin well sediments.

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490 195 Several studies have shown that the seismic records of the MSC greatly differ between the  
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492 196 Western and Eastern Mediterranean basins, and argued that it is impossible to properly correlate  
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494 197 individual sub-units (Lofi et al., 2011). Some authors have also questioned the possible  
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496 198 diachronism between both basins (Blanc, 2000; Ryan, 2008). However, the Levant has been for  
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498 199 many years at the center of debate regarding the evolution of the MSC across the entire

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507 Mediterranean ~~basin~~Basin. An example for such a long-term debate includes the formation of the  
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510 201 vast drainage systems at the Mediterranean margins and the deposition, or re-deposition, of  
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512 202 gypsum within them. An important type location for this debate is the Afik canyon along the  
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514 203 continental margin of Israel. The presence of evaporite layers at different levels along the Afik  
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516 204 canyons was brought as one of the first evidence for a substantial Messinian sea-level drawdown  
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518 205 (800 m sea-level drop; Druckman et al., 1995). However, these deposits were recently argued to  
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520 206 result ~~of~~ from evaporites recycling through slope mass-wasting, a phenomena suggested to  
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522 207 characterize the upper parts of the MSC throughout the Mediterranean (Lugli et al., 2013). The  
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524 208 wells investigated in this study were drilled in the Levant Basin, and may ~~be argued to~~ represent  
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526 209 local conditions rather than account for the entire Mediterranean Basin. However, by recovering  
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529 210 one of the most extensive evaporite deposits of the MSC, the analysis of these wells bears key  
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531 211 implications for unraveling the MSC across the entire Mediterranean.

### 532 533 212 **3. Methodology**

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536 213 This study is based on the combined analyses of well cuttings, 3D pre-stack depth-migrated  
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538 214 reflection seismics ~~reflection~~, and well-log data of two deep-water industry wells recently  
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540 215 drilled in the Levant Basin (Fig. 1). We have also used a time-migrated 2-D seismic survey  
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542 216 acquired by TGS-NOPEC Geophysical Company in 2000, and the 3-D depth-migrated Pelagic  
543  
544 217 seismic survey acquired by CGG-Veritas in 2009. Lithological and biostratigraphic data  
545  
546 218 presented in this study are from the Dolphin well (N 3628144.05 m, E 575444.97 m), drilled by  
547  
548  
549 219 the Leviathan partnership at a water depth of 1,500 m and penetrating the 1,590 m thick  
550  
551 220 Messinian evaporite section at depths of 2,026-3,616 m below sea level. The second studied well  
552  
553 221 is the Leviathan-1 ~~well~~ (N 3653455.35 m, E 553663.40 m), also drilled by the Leviathan  
554  
555 222 partnership at a water depth of 1,644 m and penetrating the 1,694 m thick Messinian evaporite  
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562  
563 223 section at depths of 2,090-3,784 m below sea level. The record presented in this study  
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565 224 supplements the 350 m section immediately below the base of the halite shown in Meilijson et al.  
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567 225 (2018). Samples were curated and archived in both the Organic Geochemistry Laboratory at the  
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569 226 University of Colorado (organic extracts) and the Department of Marine ~~Geosciences~~  
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571 ~~Geosciences~~, Leon Charney School of Marine Sciences, University of Haifa.  
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573

574 228 Drilled cuttings returns are available starting down from a depth of 2,535 m and 2,497 m in  
575  
576 229 the Dolphin and Leviathan-1 wells, respectively. The Pre-Evaporites interval of the Dolphin  
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578 230 (Meilijson et al., 2018) and Leviathan wells was sampled every 3 m. The evaporite interval was  
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580 231 sampled every ~9 m, with a total of 123 samples from the Dolphin well. Due to standard drilling  
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582 232 activities, many fallouts of ~~the~~ clastic deposits occur downhole from the lower part of the  
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584 233 ~~interbedded~~ Interbedded evaporite-Evaporite unit to the upper part of the Main Halite unit,  
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586 234 appearing as an interval of clastic deposits in the XRD log of the Dolphin well from 2,560 to  
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588 235 2,675 m. Well-log data does not respond to this high-clastic content (i.e., high RE log values and  
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590 236 low GR log values), and so does not show a shift from halite deposition. This observation  
591  
592 237 confirms that the clastic material arrives from the ~~Interbedded Evaporites~~ unit above, as drilling  
593  
594 238 fallouts into the halite interval. While not in-situ, these fallouts, together with the well logs,  
595  
596 239 allow us to interpret ~~at~~ the distinct lithological transition ~~occurring that occurs~~ at the boundary  
597  
598 240 between the Main Halite and Interbedded Evaporites unit. However, these fallouts might also  
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600 241 originate from the Argillaceous Evaporites unit above.  
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604 242 Individual cutting bits were separated by their lithology under a microscope, cleaned with  
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606 243 deionized water and 10% hydrochloric acid, dried, and then crushed in an agate pestle and  
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608 244 mortar. Fine powders were pressed and used for bulk mineralogical X-ray diffractogram (XRD)  
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610 245 analysis using a Rigaku 600 MiniFlex X-Ray Diffractometer with a CuK $\alpha$  source at 30kV / 15-

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618  
619 246 mA from 3° to 70°. Mineralogical compositions of assemblages were determined using the  
620  
621 247 ICDD PDF2 mineral database references. Next, fine powders were pressed in ~~telephone-~~Teflon  
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624 248 crucibles with X-Ray transparent mylar (which was replaced between samples). Each sample  
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626 249 was then analyzed using a Nitton X-Ray XL3 GOLDD+ Fluorescence apparatus for elemental  
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628 250 composition.

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630 251 Samples found to be bearing microfossils were investigated for their faunal assemblages,  
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632 252 which included washing and picking foraminifera from the Pre-Evaporites (detailed in Meilijson  
633  
634 253 et al., 2018) and the preparation of smear slides for the study of the diatomites interbedded  
635  
636 254 within the halite. For the latter, samples were weighed, treated several times with 10% HCl for  
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638 255 carbonate removal, and 30% hydrogen peroxide for organic matter removal, and then loaded  
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640 256 onto glass slides. A total of 50 diatom valves were counted and identified from 10 samples.  
641  
642 257 Diatoms were characterized by their habitat preferences: planktonic vs. benthic, and marine vs.  
643  
644 258 freshwater.

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647 259 We also studied the distribution of selected biomarkers (i.e., *n*-alkanes, algal steranes, and  
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649 260 bacterial hopanes) from different intervals to gain insight into variations in organic matter  
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651 261 sources and thermal alteration. Rock cuttings were cleaned and handled with solvent-rinsed  
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653 262 metal tweezers, a Dremmel 8220 wire-brush tip, spatulas, and combusted aluminum foil, and  
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655 263 then powdered with a solvent-rinsed agate mortar and pestle. Approximately 5-10 grams of  
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657 264 sample were extracted using a Dionex Accelerated Solvent Extractor (ASE 200; 100 °C; 2,000  
658  
659 265 psi) and a mixture of dichloromethylene:methanol 9:1 (v:v) until no more color was observed  
660  
661 266 (typically 3-6 extractions). Each extraction cycle included heating of the cell for 5 minutes, static  
662  
663 267 mode for 5 minutes, and flushing for 2 minutes time. A cocktail of internal standards containing  
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665 268 500 ng of D4 C<sub>29</sub> ααα (20R)-Ethylcholestane, and 1,000 ng of each 3methyl heneicosane, D14

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674  
675 269 pTerphynyl, 1-nonadecanol, behenic acid methylester (Docosanoic acid), and 2methyl  
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677 270 octadecaonic acid, was added to samples before extraction for quantitation purposes. Total lipid  
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679 271 extracts (TLEs) were combined and evaporated under a gentle nitrogen flow using a Turbovap.  
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681 272 Elemental sulfur was removed using HCl-activated copper shots. TLEs were then filtered  
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683 273 through small Pasteur pipettes filled with combusted glass wool and sand to remove impurities  
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685 274 and any copper-sulfide residues. Asphaltenes were separated from maltenes by precipitation in  
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687 275 hexanes at 4°C for 3 hours, followed by centrifugation at 2000 rpm (3x). Maltenes were later  
688  
689 276 separated into five different lipid classes by liquid chromatography on small Pasteur pipettes  
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691 277 filled with silica gel. Aliphatic (F1) and aromatic (F2) hydrocarbons were recovered with hexane  
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693 278 (3/4 dead volumes) and hexane:dichloromethylene 8:2 (v:v; 4 dead volumes), respectively. The  
694  
695 279 more polar fractions (F3, F4, F5) were eluted using dichloromethylene,  
696  
697 280 dichloromethylene:EtOAc 1:1, and EtOAc (v:v, 4 dead volumes), respectively. Aliphatic  
698  
699 281 hydrocarbons were analyzed on full scan and selected reaction monitoring (SRM) modes via gas  
700  
701 282 chromatography – triple quadrupole-mass spectrometry (GC-QQQ-MS) using a Thermo Trace  
702  
703 283 1310 Gas Chromatograph interfaced to a TSQ Evo 8000 triple quadrupole mass spectrometer  
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705 284 (GC-QQQ-MS) equipped with a split-less PTV injector and electron impact ion source. Helium  
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707 285 was used as a carrier gas with a flow rate of 1.2 ml min<sup>-1</sup>. Chromeleon 7 was used for data  
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709 286 integration. Aliphatic hydrocarbons were separated using a 60-meter DB-1MS GC column (60  
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711 287 m, 0.25 mm I.D., 0.25 µm film thickness; Agilent Technologies). For FS analysis, samples were  
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713 288 injected at 60°C and then the PTV was heated to 300°C at 14.5°C/second. The GC oven  
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715 289 temperature program was: 60°C (2 min) to 150°C at 15°C min<sup>-1</sup>, to 315 (held 24 min) at 3°C  
716  
717 290 min<sup>-1</sup>. The total GC program was 90 minutes. MS conditions were: 300°C ion source at 70eV  
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719 291 electron energy, 50µA emission current, and 15V electron lens voltage. The mass range was 50-

729  
730  
731 292 600 m/z with a dwell time of 0.2 seconds per scan. For SRM analysis, the GC oven temperature  
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733 293 program was: 60°C (0 min) to 220°C at 15°C min<sup>-1</sup>, to 315°C (held 25 min) at 3°C min<sup>-1</sup>. The  
734  
735 294 total GC program was 68 minutes. Samples were injected at 65°C and then the PTV temperature  
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738 295 was heated to 400°C at 3 °C min<sup>-1</sup>. MS conditions were: ion source temperature of 250°C;  
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740 296 transfer line temperature of 320°C, electron energy of 70eV, electron lens voltage of 35V, and  
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742 297 emission current of 35uA. Peak scanning windows ranged from 0.6 to 1 minute for 147 timed  
743  
744 298 transitions for regular and methylated steranes and hopanes, and their stereoisomers.  
745

## 746 299 **4. Evidence from the Levant Basin for an early onset of halite deposition in a deep-water** 747 748 749 300 **environment**

### 750 751 301 **4.1 Lithologic composition of the Levant deep-sea salt-giant**

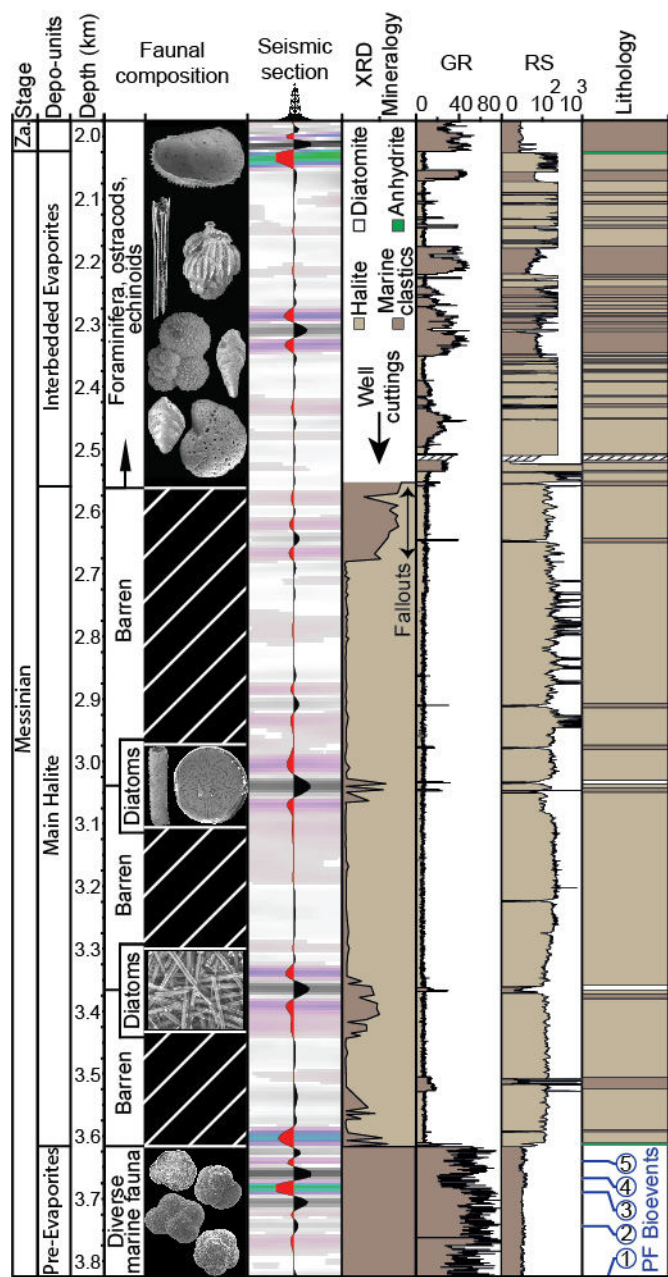
#### 752 753 754 302 *4.1.1 Pre-Evaporites*

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756 303 This interval is detailed in Meilijson et al. (2018). Here we provide a generalized summary,  
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758 304 followed by a more elaborate account of the overlying evaporites of the deep Levant Basin. The  
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760 305 ~~prePre-evaporite-Evaporite~~ interval in the Dolphin well (3850–3616 m; Fig. 2) is seismically  
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762 306 characterized by sub-horizontal and sub-parallel continuous high-amplitude reflections,  
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764 307 implying a stratified and relatively un-deformed marine succession (Meilijson et al., 2018). It is  
765  
766 308 composed of fine-grained clastic-micritic and carbonate bathypelagic sediments, primarily gray  
767  
768 309 to dark gray or greenish calcareous soft to hard shale, with several thin layers of white to light  
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770  
771 310 gray hard limestone, and light gray very fine to fine-grained unconsolidated sandstone. Diverse  
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773 311 assemblages of nannofossils, benthic and planktic foraminifera are recognized within this  
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775 312 interval.  
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788 314 *Figure 2. The MSC succession of the Dolphin well in the deep Levant ~~basin~~Basin.*  
789 315 A juxtaposed simplified display of the primary proxies used to characterize the Dolphin well  
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791 316 section (five central columns), and our depositional (left) and lithological (right) interpretations.  
792  
793 317 The attributes are (left to right): the faunal composition; the seismic response, with transparent  
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795 318 intervals representing predominantly evaporites and high--amplitude reflections representing  
796  
797 319 clastic beds (a seismic trace (center) emphasizes relative intensity of the seismic phases); XRD  
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799 320 mineralogy, showing the relative abundance of halite (bright) vs. non-halite (dark; 'marine  
800  
801  
802 321 clastics'), where the uppermost clastic interval (<2,650 m) represents fallouts from the  
803  
804 322 ~~interbedded~~Interbedded evaporitesEvaporites; the gamma ray (GR -- API units) and resistivity  
805  
806 323 (RE -- log ohm-m units) logs, color coded based on the characteristic responses to halite and  
807  
808 324 clastics. The lithological interpretation is color coded as in the attribute columns. Planktonic  
809  
810 325 foraminiferal (PF) bio-events in blue circles correspond to the following ages: 1- 7.72, 2- 7.24, 3-  
811  
812 326 6.72, 4- 6.36, and 5- 6.13 Ma (Meilijson et al., 2018).  
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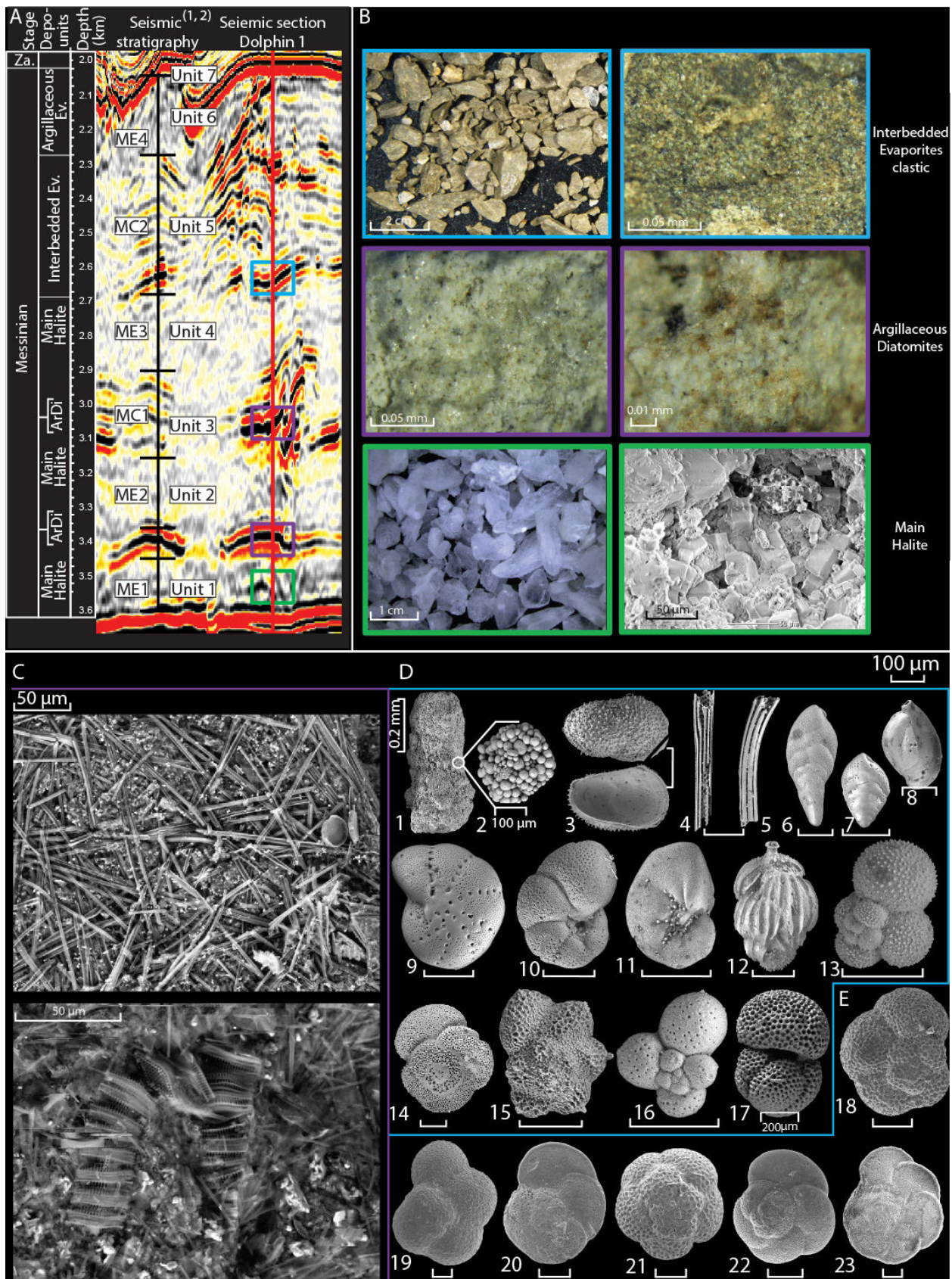


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955 330 *Figure 3. Seismic stratigraphy, common lithologies, and SEM imaging of the studied section.*  
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957 331 **A.** The seismic profile crossing the sampled Dolphin well position and its division into the MSC  
958 332 depositional units, compared to previously published seismic stratigraphy of the deep Levant  
959 333 MSC ((1) Feng et al., 2016; (2) Gvirtzman et al., 2017). ArDi ~~---~~ Argillaceous Diatomites; Ev. -  
960 334 Evaporites. Color coded rectangles corresponding to lithologies described in (B). **B.** images of  
961 335 the three main facies recognized in the Levant evaporite section: the homogeneous ~~main~~ Main  
962 336 halite ~~Halite~~ (green rectangle) made of pure halite as seen in hand specimen (left) and SEM  
963 337 imagery of cubic cleavage (right), corresponding with subdued internal seismic reflectivity in  
964 338 (A); Argillaceous Diatomite beds (purple rectangle), represented by high amplitude reflections in  
965 339 (A); and Interbedded Evaporites (blue rectangle) identified as brown marine clastics,  
966 340 characterized by interchanging low and high amplitude reflections in (A). **C.** Selected SEM  
967 341 images from the densely packed and very well preserved diatoms from the diatomite facies. **D.**  
968 342 Selected SEM images of the >63 µm size fraction of the washed residue from the Interbedded  
969 343 Evaporites unit clastic sediments (P.1-17) showing: large grains of framboidal pyrite (P.1-2),  
970 344 well-preserved ostracod valves (P.3), sea urchin spines (P.4-5), benthic foraminifera (P.6-12),  
971 345 and planktic foraminifera (P.13-17). **E.** SEM images of the planktic foraminifera used for the  
972 346 biostratigraphic age ~~-~~ model (Meilijson et al., 2018) of the ~~pre~~ Pre-E evaporites (P.18-23):  
973 347 *Neogloboquadrina* sp. (P.18), *Sphaeroidinellopsis seminulina* (P.19), *Globorotalia miotumida*  
974 348 (P.20), *Globoquadrina altispira* (P.21), *Globorotalia scitula* (P.22); *Globorotalia menardii*-4  
975 349 (P.23). All scales are 100 µm unless indicated otherwise.

987 350  
988  
989 351 Shale samples are organic ~~-~~ rich (>1 wt.% TOC) and reach peak values of 4 wt.% TOC  
990 352 immediately underlying the base of evaporite deposition (Meilijson et al., 2018). Lower values of  
991 353 gamma ray (GR) are associated with silt/carbonate-rich sediments, while higher GR corresponds  
992 354 to shale/organic-rich sediments (Fig. 2).

#### 998 355 4.1.2 Main Halite

1000 356 Here we reference our lithologic interpretation to the recently defined seismic stratigraphy of  
1001 357 the Levant MSC (units ~~Units~~ 1-6; Gvirtzman et al., 2013), and ME1-4 for the transparent and

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1010  
1011 358 MC1-2 for the high reflectivity intervals (Feng et al., 2016) (Fig. 3). Different velocity models  
1012  
1013 359 reported high seismic velocities of 4200-4400 m/s (Gvirtzman et al., 2013a), 3850-4240 m/s  
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1016 360 (Reiche et al., 2014), and 4400-4600 m/s (Feng et al., 2016) for the seismic transparent layers,  
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1018 361 interpreted as representing the halite facies. Here we advocate this interpretation by providing the  
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1020 362 first semi-quantitative XRD analysis (Fig. 4) of well cuttings spanning the transparent high  
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1022 363 velocity layers.

1024 364 The Main Halite unit in the vicinity of the Dolphin (3616- 2755\_m) and Leviathan-1 (3759-  
1025  
1026 365 2800 m) wells is characterized by low seismic reflectivity, which is internally interrupted by  
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1028 366 several main high reflectivity bands (Figs- 5, 6). These instances are clearly recognized in the  
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1030 367 well\_-logs (Fig- 2, 5), and represent a different facies within the hyper-saline deposits, described  
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1032 368 ~~aheadbelow~~. Using XRD analysis coupled with SEM (Fig. 4), we conclude that the transparent  
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1034 369 intervals are indeed composed of nearly pure (~~←~~( $\geq$ 90%) halite (Fig. 4), with minor quantities of  
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1036 370 anhydrite, magnesite and barite. Anhydrite ~~appears is also present~~ as a relatively thin bed ( $<3$  m)  
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1038 371 at the base of the Main Halite section, where it represents the transition to the Main Halite.  
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1040 372 Anhydrite ~~also further~~ appears in the upper, more clastic ~~Interbedded-Evaporites~~ part of the  
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1042 373 section (~~2560-2025 m~~; Fig. 2), as is also reported from the same stratigraphic ~~level-interval~~ by  
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1044 374 Gvirtzman et al. (2017). The halite is clear to milky white with a firm to very hard  
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1046 375 macrocrystalline structure (Fig. 3), while the anhydrite minerals are white, soft to firm, nodular  
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1048 376 and amorphous to massive. A sharp transition from the Pre-Evaporites to halite is marked by a  
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1050 377 decrease in GR well log counts from 53 API to 12 API as well as a sharp increase in the  
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1052 378 ~~formation-resistivity-(RE)~~ well log reaching 10,000 ohm (Fig. 2; see also Feng et al., 2016).  
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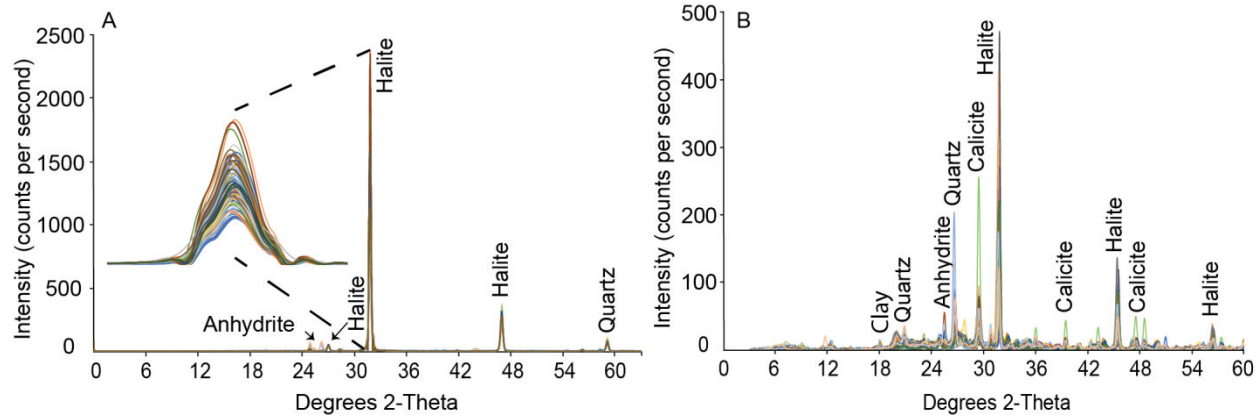


Figure 4. X-ray diffraction results

**A.** Overlaid (color coded) XRD analysis of 89 halite samples from the Dolphin well produced diffractograms, which are practically identical. The main halite peak is zoomed for emphasis. **B.** Higher variability is recorded both in peaks location and intensity when analyzing samples from the non-evaporitic marine sediments, sampled along the section between the depth of 3,616 m to 2560 m.

These values remain relatively constant within the halite deposits, although inter-halite variations are observed, mainly on the RE log. The pronounced high-amplitude reflection at ca. 3520 m (Dolphin well; Figs- 2, 3), also recognized as an increase in the GR well -logs, represents a short-term return to the clastic Pre-Evaporites facies although with low abundance and poorly preserved foraminiferal content. This interval is not part of the Argillaceous Diatomites facies.

#### 4.1.3 Argillaceous Diatomites

Distinct reflective layers appear within the seismic transparent halite expressions, correlating with relatively lower velocity zones in the seismic velocity models developed for the deep Levant Basin MSC strata (e.g., 3800-4000 m/s in Gvirtzman et al. (2013); 3650-4030 m/s in Reiche et al. (2014)). These reflective layers are easily identified across the study area (Figs- 5, 6).

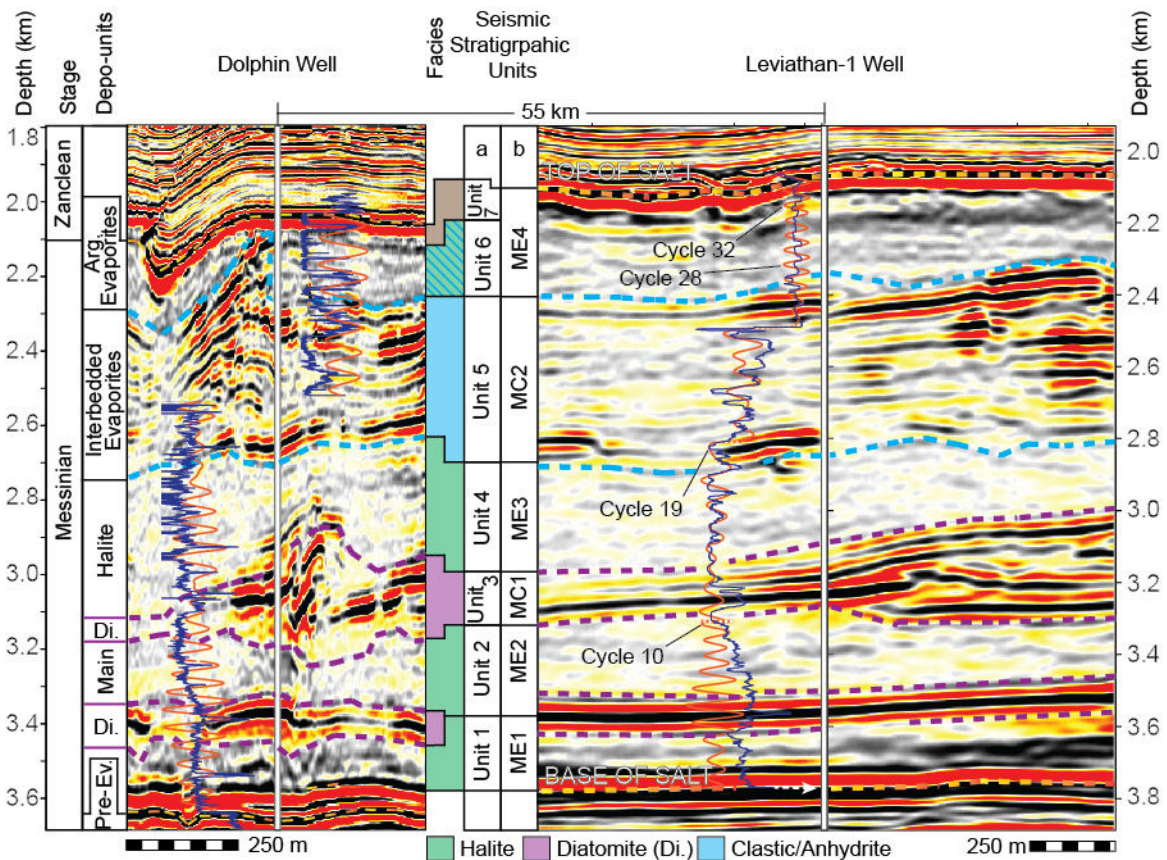
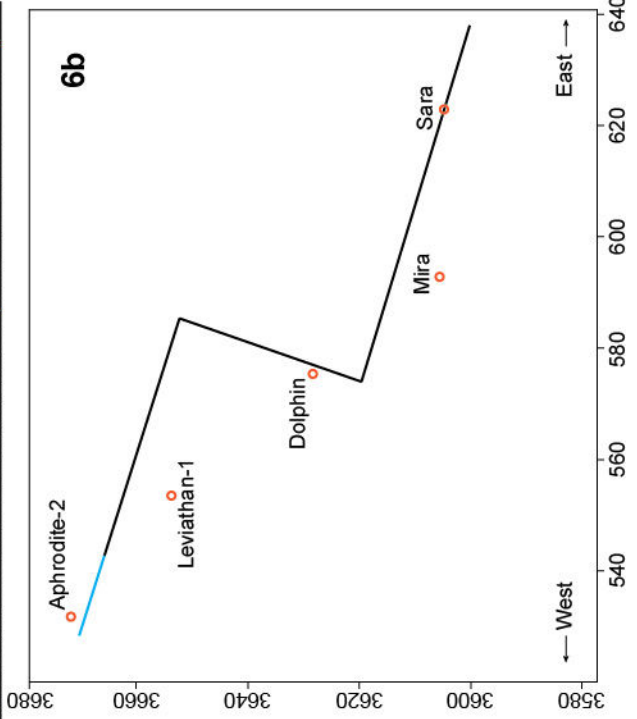
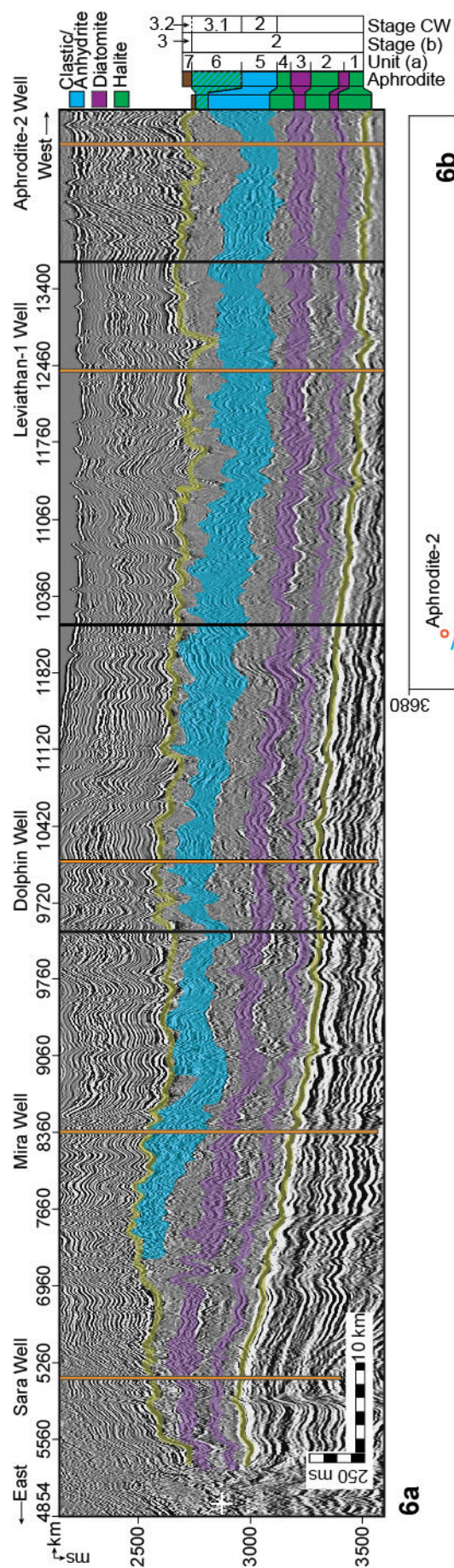


Figure 5. Geophysical data and seismic stratigraphy of the Dolphin and Leviathan-1 wells.

Depth-migrated sections crossing the Dolphin (left) and Leviathan-1 (right) wells (marked by a vertical white line). Overlaid on the sections are the well logs (blue curve left to the well), and the filtered well-log cycles superimposed on the target curves (orange). The depth and lithostratigraphic units (this work) related with the sampled Dolphin well are displayed on the left, and the depth related with the Leviathan-1 well is displayed on the right. Data columns in the middle are seismic-stratigraphic units from (a) Gvirtzman et al. (2013, 2017), and (b) Feng et al. (2016). Note the relatively deformed area of the Dolphin well relative to the more conformal vicinity of the Leviathan-1 well.

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1235 409 *Figure 6. A composite seismic section linking the commercial wells across the Levant Basin.*  
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1237 410 A composite time-migrated seismic section (a), and location map (b), combining three 2D  
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1239 411 traverses of the TGS survey (dark line) with a transect through the Pelagic 3D volume (blue line)  
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1241 412 across the Levant Basin, all plotted at a common scale with a vertical exaggeration of ca. x10.  
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1243 413 Orange vertical lines note the positions of the wells discussed in the text, while black lines note  
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1245 414 the section stitches, primarily at turning points. The wells are projected laterally onto the seismic  
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1247 415 profiles by up to 10 km (in the case of the Leviathan-1 well). Note the similar relative spatial  
1248  
1249 416 thickness of the diatomite beds (purple) in comparison with the largely varying thickness of the  
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1251 417 Interbedded Evaporites (blue). Stage CW (current work); Stage (b) (Manzi et al., 2018); Unit (a)  
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1253 418 (Gvirtzman et al., 2013; 2017).  
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1258 420 In the Dolphin well, this seismic facies includes five seismic high-reflectivity bands,  
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1260 421 corresponding to peaks in the GR and troughs in the RE well-logs, appearing within the Main  
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1262 422 Halite interval between 3375 and 2560 m (Fig. 2). Using a GR value of 20 API as an upper  
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1264 423 cutoff value for determining the location and thickness of these intervals, results in estimated bed  
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1266 424 thicknesses of 0.9-2.4 m (Fig. 2). Of the 1,056 m Main Halite interval in the Dolphin well, the  
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1268 425 non-halite sediments form a regional cumulative thickness of 25-40 m (see also Feng et al.,  
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1270 426 2016; Gvirtzman et al., 2013). At the macro-scale, the content of these layers appears as light  
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1272 427 gray to white, soft to firm, porous, and occasionally fibrous. SEM imaging and smear-slide  
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1274 428 analyses indicate that the rock-mass is made of densely packed, very well-preserved, and intact  
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1276 429 diatoms (Fig. 3), and fine-grained terrigenous sediments (Fig. 4). No other transported or local  
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1278 430 faunal remains were recognized. Identified diatoms include abundant marine planktonic genera,  
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1280 431 such as *Coscinodiscus*, *Asteromphalus*, and *Actinoptychus* (*sensu* Tomas, 1996).  
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1291 432 XRD analysis from available samples of these high-amplitude intervals confirms the log data  
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1293 433 response and shows an increase in terrigenous grains, mainly composed of quartz, calcite, some  
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1295 434 clay minerals, and low amounts of anhydrite, dolomite and magnesite. (Fig. 4). Halite appears  
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1298 435 within these samples in a high relative abundance, reaching 45% (Figs. 2, 4).  
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1300 436 Due to the nature of well-cuttings, samples from these intervals were only retrieved from the  
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1302 437 two thickest beds, at 3367.7 m of the Dolphin well with a thickness of 2.4 m, and the two  
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1304 438 adjacent beds at 3047 and 3034 m with a cumulative thickness of 2.1 m. These intervals are also  
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1306 439 represented by bands of much higher seismic reflectivity than the thin (1.2-1.4 m), overlying  
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1308 440 intervals at 2910 and 2646.5 m. Consequently, the two upper intervals might be the same  
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1310 441 diatomite facies, or only represent marine clastic sediments.  
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#### 1312 442 *4.1.4 Interbedded Evaporites*

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1315 443 This facies is represented in the seismic sections by high-amplitude reflections interbedded  
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1317 444 with nearly transparent intervals with weak internal reflections (Fig. 3), interpreted in previous  
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1319 445 studies to represent an alternation of clastic sediments and evaporites (Gvirtzman et al., 2013a;  
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1321 446 Feng et al., 2016). More recently, Gvirtzman et al. (2017) and Manzi et al. (2018) presented  
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1323 447 further evidence based on well logs from deep-basin wells in the region (Aphrodite), or by  
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1325 448 correlation to more proximal well sections (Hannah-1), showing that this interval mostly consists  
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1328 449 of shale, sand, anhydrite, and halite. The Interbedded Evaporites unit correlates to Unit 5 in  
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1330 450 Gvirtzman et al. (2013). It covers 2560-2025 m in the Dolphin well, and 2548-2276 m in the  
1331  
1332 451 Leviathan-1 well. The GR well log in the Leviathan-1 well indicates 3 m to 20 m thick clastic  
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1334 452 beds, interbedded with evaporites varying in thickness from 6 m to 30 m. A relatively large  
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1336 453 diameter wellbore used while drilling this interval might have reduced the GR signal and thinner  
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1338 454 clastic beds might not have been detected.  
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1347 455 Due to drilling limitations, the material made available from this interval is partial, and the  
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1349 456 only sampled sequence consists of the lowermost part above 2560 m in the Dolphin well. We  
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1351 457 consider grains from this interval as fallouts from the Interbedded Evaporites unit, confirmed by  
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1353 458 the absence of any indications for a clastic interval in the well-log and seismic data from the top  
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1355 459 of the Main Halite interval, where these grains appear. The samples are made of hard, light to dark  
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1357 460 brown sandy shales (Fig. 3). The grain composition of the >63 µm washed residue is very  
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1359 461 different compared to the underlying Main Halite or Argillaceous Diatomite facies. It contains a  
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1361 462 higher amount of sub-rounded larger sand grains compared to the diatomite facies, different  
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1363 463 types of pyrite including large agglutination of pyritohedrons reaching several mm in size, and a  
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1365 464 diverse faunal composition (Fig. 3). The latter includes few mollusk fragments, ostracods,  
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1367 465 ~~echinoid~~ ~~sea-urchin~~ spines and a relatively rich assemblage of benthic and planktic foraminifera  
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1369 466 (Fig. 3). The most common foraminifera are different *Globigerinoides* species, *Orbulina*  
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1371 467 *universa* and *Sphaeroidinellopsis seminulina* (younger than 15 Ma; Berggren et al., 2006). Older  
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1373 468 Cretaceous to Eocene foraminifera species are also present, indicating reworking processes, most  
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1375 469 likely from exposed basin margins. These include *Parasubbotina pseudobulloides* (Danian-  
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1377 470 Selandian; Fig. 3.D.13), *Plummerita hantkeninoides* (Maastrichtian; Fig. 3.D.15), and *Subbotina*  
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1379 471 *triloculinoides* (Paleocene; Fig. 3.D.17). While no overlying samples exist, this interval was  
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1381 472 logged and a reliable lithological interpretation is presented by extrapolating the coupling  
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1383 473 between sample analysis (XRD and micropaleontology) and the log data from the lower to the  
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1385 474 upper part of the section (Fig. 2). The clastic input is estimated from the geophysical data as  
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1387 475 ~40% of the 535 m thick unit in the Dolphin well. However, due to local deformations in the  
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1389 476 Dolphin well area, the Interbedded Evaporites are displaced and ~~reach-at~~ their top is reached at  
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1391 477 the top of the MSC section.  
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1404 478 ~~Comparing Comparison with~~ Manzi et al. (2018) suggests that, Unit 6 is not represented in  
1405  
1406 479 the Dolphin well but ~~rather that~~ Unit 5 reaches-marks the top of the section (Fig. 5). However,  
1407  
1408 480 seismic and well-log interpretation indicates that in the Leviathan-1 well another ~200 m of  
1409  
1410 481 evaporites appear above the Interbedded Evaporites, ~~correlating which corresponds~~ to Unit 6 in  
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1412 482 Manzi et al. (2018). There, the Interbedded Evaporites (Unit 5) are 260 m thinner than in the  
1413  
1414 483 Dolphin well (Fig. 5). This discrepancy is presumably the result of post-depositional halokinetic  
1415  
1416 484 deformation and imbrication of ~~unit~~ Unit 5 in the Dolphin well, as imaged in the seismic data  
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1418 485 (Fig. 5).

#### 1420 486 *4.1.4-5 Argillaceous Evaporites*

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1423 487 This interval was not sampled in any of the Levant Basin studies and ~~any-its~~ interpretation of  
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1425 488 ~~it in the present~~ is only based on the interpretation of seismic and well-log data. In the  
1426  
1427 489 Leviathan-1 well this interval covers the ~~top uppermost part~~ of the evaporites at-between 2,090-m  
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1429 490 and to 2,320 m (Fig. 5). The transparent reflective character of this interval in the seismic section  
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1431 491 includes cyclic darker bands. The unit appears to be composed of clastic sediments, probably  
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1433 492 clays, silts and sands, which are characterized by GR values of 7<sub>api</sub> to 15<sub>api</sub> API. Intervals of ca.  
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1435 493 zero GR are interpreted as argillaceous anhydrite. Gvirtzman et al. (2013; 2017), Feng et al.  
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1437 494 (2017), and Manzi et al. (2018) refer to this interval as Unit 6, ~~and it which~~ is generally lumped  
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1439 495 with the underlying halite as part of the evaporite unit. Regionally, the presence of Unit 6 is  
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1441 496 limited to the westernmost and deeper areas of the basin, while it is truncated to completely  
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1443 497 removed landward to the east (Fig. 6). The amount of truncation on Unit 6 gradually increases  
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1445 498 eastwards, eroding also Units 5-2 at the eastern parts (Gvirtzman et al., 2013, Feng et al., 2017;  
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1447 499 the current study). Both the Dolphin and the Leviathan wells are within the deeper areas in which  
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1449 500 Unit 6 is present, but due to local deformations it might be underrepresented in the Dolphin well.  
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1459 501 A 5 m clastic and ~~anhydrate-anhydrite interval bed~~ defines the top of ~~tops the MSC~~ this unit,  
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1461 502 ~~marked by a~~ nearly transparent seismic interval in the Leviathan-1 well, as indicated by a sharp  
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1464 503 drop in GR and drilling penetration rate relative to the overlying Pliocene sediments. This  
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1466 504 anhydrite interval ~~might be~~ most likely part of Unit 7 in Gvirtzman et al. (2018), or the Nahal  
1467  
1468 505 Menashe in Madof et al. (2019).

#### 1470 506 **4.2 Chronology of halite deposition and well log frequency analysis**

1473 507 In order to attain a direct age control on the duration of halite deposition, the halite samples  
1474  
1475 508 were washed and inspected for microfossils, prepared as smear slides, and examined under SEM  
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1477 509 in search for the preservation of eukaryotic life in the evaporites, which failed.

1479 510 We also measured the Sr<sub>2</sub>-isotopic composition of evaporite samples in order to compare them  
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1481 511 with the well-established Sr isotope stratigraphy constructed from elsewhere in the  
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1483 512 Mediterranean (e.g., Topper et al., 2011; Roveri et al., 2014; Flecker et al., 2015). This published  
1484  
1485 513 dataset shows that Sr<sub>2</sub>-isotope data from stage 1 lies mainly within error of the ocean<sub>2</sub>-water  
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1487 514 curve (McArthur et al., 2012), suggesting that the Mediterranean was connected to the global  
1488  
1489 515 ocean during the initial phases of the MSC (e.g., Roveri et al., 2014; Flecker et al., 2015). During  
1490  
1491 516 stages 2 and 3 the Mediterranean's Sr record diverges from ocean<sub>2</sub>-water values towards much  
1492  
1493 517 lower ratios that reflect a substantially smaller connection to the global ocean and dominance of  
1494  
1495 518 fresh<sub>2</sub>-water sources such as the Nile, Rhone, and input from the Paratethys, particularly during  
1496  
1497 519 the Lago Mare phase (e.g., Roveri et al., 2014; Flecker et al., 2015). Sr<sub>2</sub>-isotope data from the  
1498  
1499 520 lowest Pliocene are again within error of ocean<sub>2</sub>-water values, indicating an abrupt transition  
1500  
1501 521 back to full connectivity after the MSC (e.g., Roveri et al., 2014; Flecker et al., 2015). Despite  
1502  
1503 522 the wide geographical distribution of the Mediterranean samples from which this published Sr<sub>2</sub>-  
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1505 523 isotope stratigraphy has been constructed, the pattern appears to be consistent, indicating that the

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524 controlling factor was Mediterranean-Atlantic exchange and that the Mediterranean behaved as a  
525 single basin throughout the MSC (Flecker et al., 2015). However, the dataset does not include  
526 samples from these deep-water Eastern Mediterranean sites as they were previously not  
527 available; ~~and~~ it therefore makes sense to compare new analyses from these locations with the  
528 existing Sr-chemostratigraphic scheme.

529 Halite is highly soluble and it is therefore challenging to clean samples prior to analysis. We  
530 used the basic method described in Gvirtzman et al. (2017) and Manzi et al. (2018), with  
531 additional eleven different techniques (Fig. S1, Table S1) for attempting to isolate the halite  
532 ~~grains-crystals~~ from any contaminant phases coating the samples such as clay or industrial  
533 drilling additives. The data generated for each of the nine different samples analyzed is highly  
534 variable, ranging from a few values within error of Late Miocene ocean water (McArthur et al.,  
535 2012), to substantially higher values (Fig. S1, Table S1). There is no consistency between the  
536 data generated and the technique used for dissolving the halite (Fig. S1, Table S1), suggesting  
537 that we have not been able to reliably isolate the halite from contaminant phases coating the  
538 crystals by any of the methods used. We therefore conclude that none of this data should be  
539 considered as representing a primary record of Eastern Mediterranean water at this time.

540 Similar high values have been reported for halite from other industrial wells in the Levant  
541 Basin (Gvirtzman et al., 2017; Manzi et al., 2018). Manzi et al., (2018) attributed the  
542 anomalously high values to “local, diverse, short-term Sr input”, but did not specify what this  
543 input might be. One possibility is that these published halite values from industrial cuttings may,  
544 like our data, ~~also~~ be contaminated. We conclude that a robust Sr-isotope record for the deep-  
545 basin halite deposits will only be achieved either by establishing a reliable method for removing

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546 contaminant phases or by recovering halite samples without the use of industrial drilling fluids,  
547 e.g., through scientific drilling (Camerlenghi et al., 2014).

548       Next, we attempted to construct a chronostratigraphic framework for the Levant MSC  
549 deposits based on astrochronological tuning. We carried out spectral analysis of GR and RE  
550 well-logs to correlate the Levant MSC section to astronomical target curves, and the more  
551 proximal to onshore Mediterranean MSC deposits. REDFIT spectral analyses (Schulz and  
552 Mudelsee, 2002) of the Dolphin and Leviathan-1 well-log data from the base to the top of the  
553 evaporite unit (3616-2025 m in the Dolphin well, divided into three intervals for spectral  
554 analysis; Fig. S2) indicates statistically significant, periodical signals in the RE and GR logs.  
555 However, the GR produces a weaker signal than the RE log within the massive halite intervals.  
556 This is expected, as pure halite does not contain the elements U, Th, and K and their decay series  
557 responsible for natural GR radiation emitted by rocks. However, several examples indicate how  
558 different log responses occur within halite sequences. For example, inner-halite variations such  
559 as thin clay ~~laminas~~ laminae caused by microstratification within the brines might occur  
560 (Sonnenfeld, 1983). Alternatively, thin sulphate layers (Biehl et al., 2014) have also been shown  
561 to produce log-responses.

562       Each of the analyzed log segments is characterized by several frequency peaks exceeding the  
563 chi 95% confidence interval (Fig. S2). Each segment was bandpass filtered according to these  
564 frequencies, and the fit of the filtered version to the original well-log was examined, ultimately  
565 selecting the best-fit result for subsequent analysis. Both logs are composed of significant and  
566 approximately overlapping periodical frequencies, with an average cycle thickness of ~50 m  
567 (Fig. S2). While the RE log appears to be more attuned to inner-halite variations in the Main  
568 Halite interval, the GR log is more consistent and provides a more reliable fit to the well log

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1628 569 target curve in the Interbedded Evaporites units above 2833 m. Consequently, the Dolphin well  
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1630 570 cyclostratigraphy is constructed from information derived from the GR and RE logs that cover  
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1632 571 the lower and upper parts of the section (Fig. S2). The lower part of the Main Halite interval  
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1634 572 (cycles 1-11; Fig. S2) is not very well represented by the Gaussian filter, with some five cycles  
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1636 573 that fit well with the target curve. The upper part of the Main Halite interval is best filtered by  
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1638 574 using the RE log with a bandwidth of 49 m (cycles 12-24; Fig. S2). The cycles within the upper  
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1640 575 part of the section in the interbedded-Interbedded evaporite-Evaporite interval are picked up  
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1642 576 relatively clearly by the GR log (cycles 25-32; Fig. S2). However, as the Dolphin well section  
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1644 577 from the Interbedded Evaporites and above experienced significant deformation (Figs- 5, 6), the  
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1646 578 well-log cyclostratigraphy of the upper part of the studied section is not reliable in this well.

1648  
1649 579 Several frequency peaks exceeding the chi 95% confidence interval were also identified in  
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1651 580 the Leviathan-1 well-log analysis, where deformation was minimalis reduced and Unit 6 is  
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1653 581 represented (Figs- 5, 6). The RE log was cleaned from clear-outlier spikes and used for bandpass  
1654  
1655 582 filtering. The original log includes several short intervals in which values go-range from 10's or  
1656  
1657 583 100's of ohm\*m to extremely high 18,000+ ohm\*m values, masking cyclic trends in the data.  
1658  
1659 584 Fig-ure 5 includes-shows the cleaned RE log overlain on the seismic data. There is a much-  
1660  
1661 585 improved fit between the log and filtered cycles, relative to the Dolphin well-filtering, with only  
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1663 586 a few examples of a misfit between the two. A good fit is also generally apparent between the  
1664  
1665 587 seismic signal and the well-log response. The Main Halite interval includes 19 cycles, in which  
1666  
1667 588 cycles 4 and 5 are within the first Argillaceous Diatomite beds, and cycles 11-13 are within the  
1668  
1669 589 second. The cycles within the Interbedded Evaporite interval are picked up relatively clearly by  
1670  
1671 590 the RE log (cycles 19-27; Fig. 5). The-In the Argillaceous Evaporites toping-in the uppermost

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1684 591 part of the studied section in the Leviathan-1 well, the RE log response fits with banding in the  
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1686 592 seismic data, which is also picked by bandpass filtering (cycles 27-33; Fig. 5).

1687  
1688 593 Consequently, bandpass filtering of the well\_-logs results in ~33 cycles from the base to the  
1689  
1690 594 top of the evaporites sequence in the Levant Basin. In the next two sections, we present different  
1691  
1692 595 findings supporting the occurrence of lithological cycles along the studied section, followed by  
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1694 596 the astrochronologic interpretation of these cycles in the discussion section.

### 1695 1696 597 **4.3 Cyclicality of seismic reflective phases**

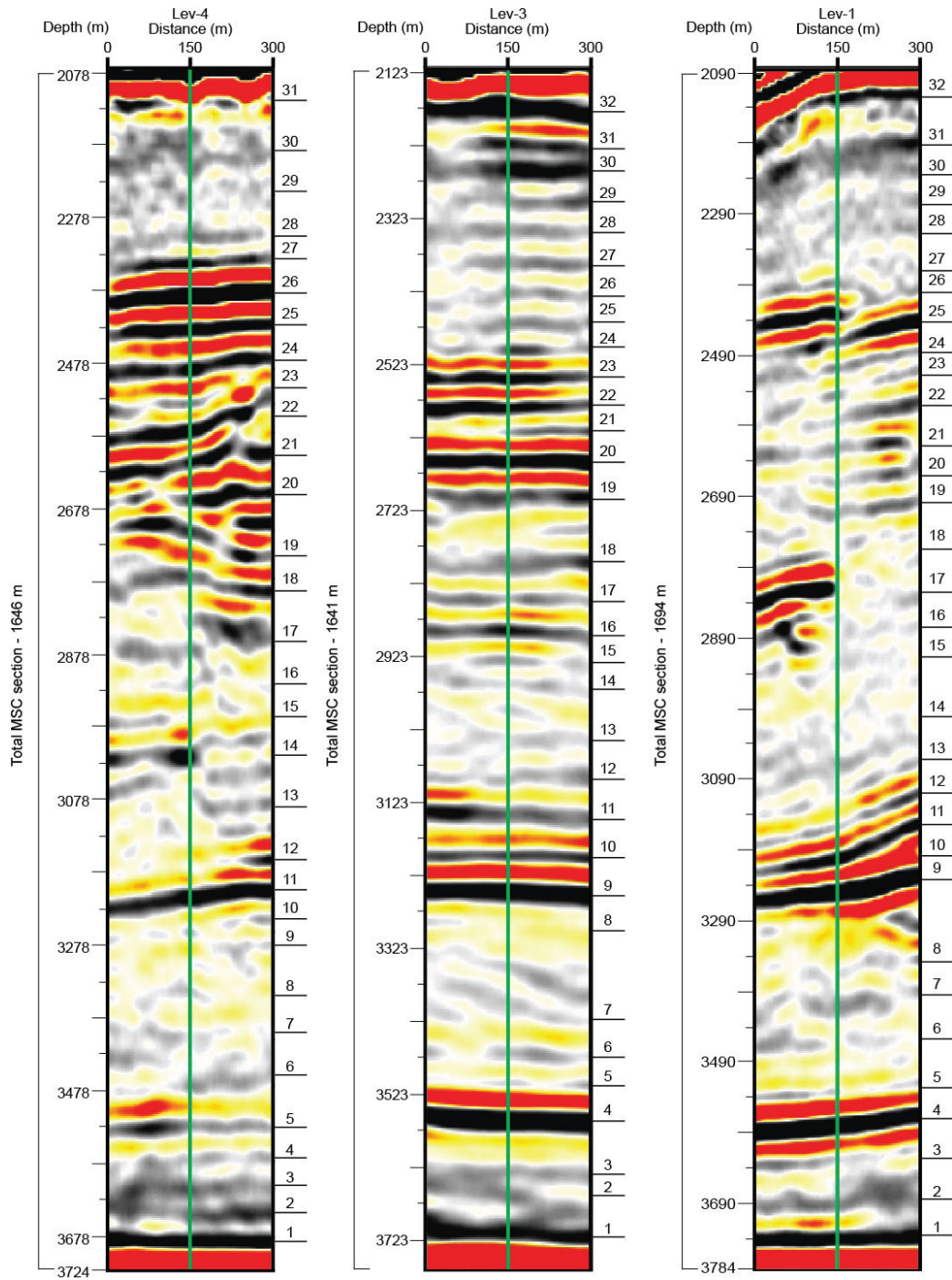
1698  
1699 598 Modern high-quality 3D seismic imagery represents a new frontier for astronomical  
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1701 599 calibration, potentially adding a chronological time-frame for seismic stratigraphy. However, in  
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1703 600 most marine settings, precession-scaled cycles are registered as-at a thicknesses-to-cycles ratio  
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1705 601 which has a much higher resolution than the seismic data. Yet, several studies show a good  
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1707 602 match between the number of precession-induced astronomic cycles and the number of positive  
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1709 603 vs. negative seismic phases within MSC deposits (Driussi et al., 2015; Geletti et al., 2014). This  
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1711 604 is explained by the considerably higher sedimentation rates that characterize evaporite deposits,  
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1713 605 relative to the much lower rates typical of normal-marine clastic or carbonate deposition. The  
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1715 606 higher sedimentation rates result in an improved alignment between the spacing, or resolution, of  
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1717 607 lithologic variations and the resolution of the seismic imagery. As orbital forcing was repeatedly  
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1719 608 identified as determining lithological variations during the MSC (e.g., Krijgsman et al., 1999;  
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1721 609 Ochoa et al., 2015; Roveri et al., 2014a; Sierro et al., 2001; van den Berg et al., 2015), seismic  
1722  
1723 610 data recording these variations can be used with caution for strengthening the well-log  
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1725 611 astronomical tuning-based age models. This is not the case for the Pre-Evaporites in this area,  
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1727 612 which deposited at an average sedimentation rate of 11.4 cm/kyr and a cycle thickness of around  
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1729 613 2-3 m, as shown by Meilijson et al. (2018). This thickness is below the resolution of the seismic  
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614 data. Here, we use the seismic 3D data for additional validation of our results from well-log  
615 curves based on REDFIT spectral analysis and bandpass-filtering within the Main hHalite and  
616 overlying Interbedded Evaporites intervals.

617 In practice, the seismic tuning analysis was performed by counting the number of reflectivity  
618 phases on three different sections where wells were drilled within the 3D geophysical dataset of  
619 the study area (Figs. 1, ~~and~~ 7). Yet, as halokinetic deformation affected the Levant deep-basin  
620 evaporites, and particularly their upper units (Gvirtzman et al., 2013a), spatial variations are  
621 expected even considering a scenario of regionally uniform deposition. Such variations in the  
622 number and thickness of cycles are indeed observed when comparing different seismic sections,  
623 reflecting the local variabilities (Fig. 7). In total, a consistent number of ~30 reflectivity cycles is  
624 identified in different locations (~~Fig. 7~~), which is in agreement with the cyclicity identified  
625 through well-log spectral analysis.



626

627 *Figure 7. Seismo-cyclostratigraphy of three seismic profiles around wells in the study area.*

628 Three depth-migrated profiles that are aligned with wells in the central Levant. Black lines  
 629 with numbers on the right hand side of each seismic profile represents a reflectivity phase (black)  
 630 cycle count along the section. Left bar shows actual depth for each section and the total depth  
 631 from base to top of the MSC section in each well.

#### 4.4 Elemental variations within evaporite samples

The wellbore cuttings do not allow recognition of macro-scale sedimentological features, which may reflect the cyclicity identified in the well logs and seismic data within the halite sequence. Tuning of marginal MSC sections has been done based on lithological transitions, such as branching selenite to massive selenite, or chaotic deposits to clastic evaporites in stages 1-3 (e.g., Roveri et al., 2014a), or diatomite-shale-carbonate transitions in the Pre-Evaporites (Ochoa et al., 2015; Sierro et al., 2001). Here, we explore whether minor inner-halite chemical variability down-section can account for the filtered cycles and variable log response within apparently massive and homogenous halite. Other Miocene intervals of homogeneous lithology have also been shown to contain cyclic changes in the chemical composition of the sediments (van den Berg et al., 2015), which are assumed to represent shifts in the depositional environment ~~shifts~~. We hypothesize that these variations, if present in deep Mediterranean basins, could correspond to: 1) disparities-variations in riverine runoff and associated influx of clastic material into the basin, and/or 2) shifts in the degree of evaporation determining the type of deposited evaporites. Both of these drivers can be related to orbital forcing (Marzocchi et al., 2015; Simon et al., 2017).

We observe a relatively low correlation ( $R^2=0.46$ ; Fig. 8A) between Fe and K in the Levant halite samples, which is not in agreement with the occurrence of continentally-derived material transported to the Eastern Mediterranean. In contrast, a high elemental correlation ( $R^2=0.91$ ; Fig. 8B1) is observed between S and Ca, which confirms that low and variable amounts of minerals rich in  $\text{CaSO}_4$  (i.e., gypsum and anhydrite) represent an integral part of evaporite deposition in the Main Halite of the deep Levant Basin.

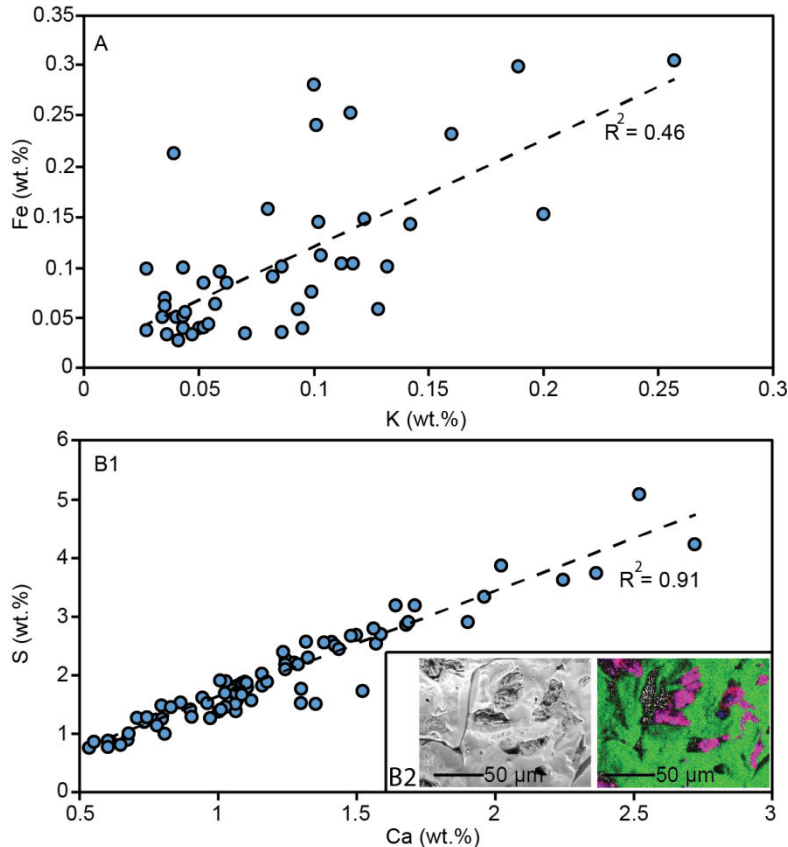


Figure 8. X-ray fluorescence elemental analysis of the Levant evaporites

Results of XRF elemental analysis are shown for 77 halite samples for specific elemental composition. (A) Note the low correlation between iron and potassium, while (B1) shows a high sulfur to calcium correlation. The high correlation between sulfur and calcium is corroborated by SEM-EDS imagery and element maps (halite sample from 3058 m; (B2)) showing the distribution of Na (green), Ca (blue) and S (red). Note that the indicating the occurrence of gypsum microcrystals (purple; B2) within cavities of the larger and much more common halite crystals has a distinct swallowtail twinned microcrystals pattern.

This notion is further confirmed by the recognition of anhydrite-calcium sulfate microcrystals minerals and small-scale but distinct swallowtail twinned microcrystals fabrics within the halite cuttings (Fig. 8B-2). Note that not all halite grains crystals included a similar deposition precipitation of calcium sulfates in small pores. We suggest that shifts in the amount of gypsum

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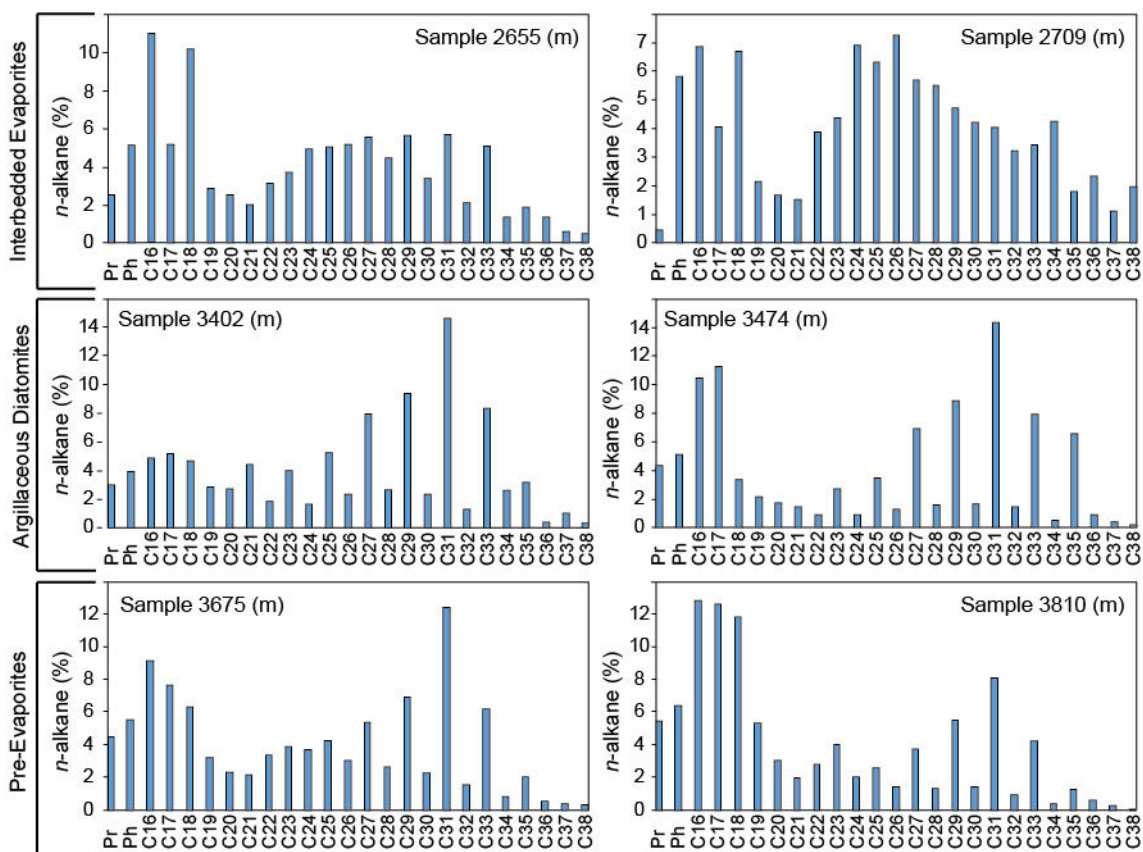
668 or anhydrite deposition~~al~~ along the section might correspond with the cycles obtained by well-  
669 log spectral analysis.

#### 670 4.5 Organic geochemistry as a stratigraphic marker

671 Biomarker data allow~~s~~ us to identify sources of sedimentary organic matter preserved in the  
672 cuttings as well as to gain insights into its thermal history. We observed distinct differences in  
673 the biomarker distribution found in the Pre-Evaporites, the Argillaceous Diatomites within the  
674 Main Halite deposits, and the overlying Interbedded Evaporites interval. The *n*-alkanes ranged~~d~~  
675 from *n*-C<sub>16</sub> to *n*-C<sub>38</sub> (Table 1, Fig. 9), and their distribution ~~varied~~varies between samples. For  
676 example, while short- and long-chain alkanes ~~were~~are more predominant in the Pre-Evaporites  
677 and the Argillaceous Diatomites, mid-chain alkanes ~~were~~are more prominent in the Interbedded  
678 Evaporites. Additionally, the carbon preference index (CPI) of long-chain *n*-alkanes, which  
679 portrays the degree of oddity in the distribution of the different *n*-alkanes, ~~varies~~d around 5-7 in  
680 the Pre-Evaporites, 4-12.3 in the Main Halite (Argillaceous Diatomites) interval, and around 1.9-  
681 2.9 in the Interbedded Evaporites (Table 1; Fig. 10). ~~The CPI reports on the degree of oddity~~  
682 ~~between the distribution of the different *n*-alkanes.~~ The Argillaceous Diatomites also contain the  
683 lowest Pr/Ph ratios (Table 1, Fig. 10) compared to other samples. The relative abundance of  
684 long-chain *n*-alkanes (C<sub>25</sub>-C<sub>35</sub>) ~~was~~is more elevated within the Argillaceous Diatomites and  
685 ~~pre~~Pre-evaporiteEvaporite. This ~~was~~is reflected in the ratio of long chain (C<sub>25</sub>-C<sub>37</sub>) to short  
686 chain (C<sub>16</sub>-C<sub>21</sub>) *n*-alkanes, which ~~maximized~~ in the Argillaceous Diatomites (1.9), followed by  
687 the Interbedded Evaporites (1.6) and the Pre-Evaporites (1.2). The C<sub>31</sub> *n*-alkane ~~was~~is commonly  
688 is the most dominant homologue.

689 Selected hopane- and sterane-based thermal maturity indices (Table 2; Fig. 11; Peters and  
690 Moldowan, 1993; Rullkötter and Marzi, 1988; Peters et al., 2005) also indicate major differences

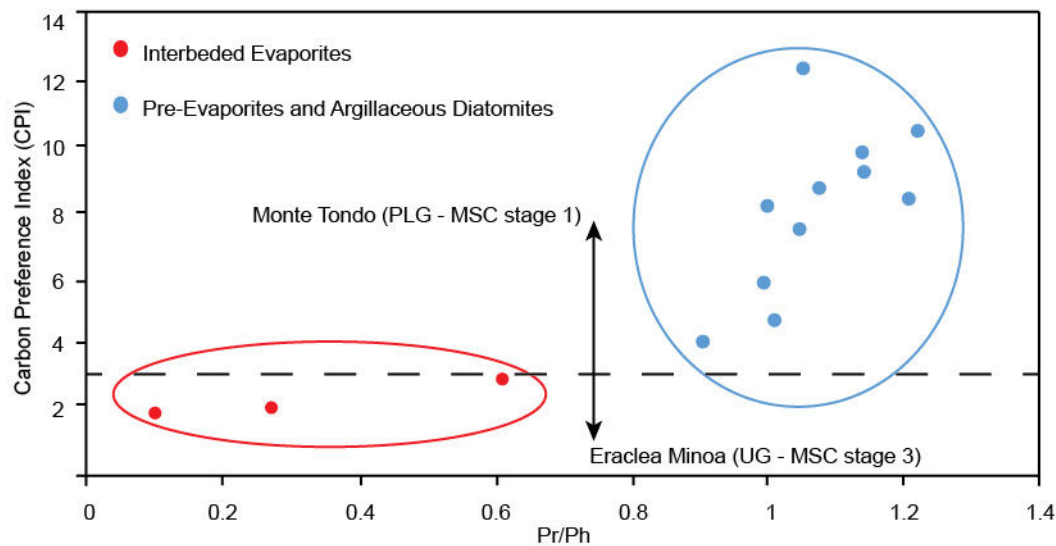
691 between samples from the Pre-Evaporites and Argillaceous Diatomites, relative to those from the  
 692 lower part of the Interbedded Evaporites ~~interval~~. As summarized in Table 2, the diatomite facies  
 693 exhibit the lowest thermal maturity values, to be followed by the Pre-Evaporites, and while much  
 694 more mature ~~indicative~~ indices are reached in the overlying Interbedded Evaporites. This is  
 695 clearly indicated by the presence of hopanes with the biological  $\beta\beta$  configuration, in addition to  
 696 low values of the  $C_{31}$  S/R hopanes ratio and the  $C_{28}$   $\alpha\alpha$  20S/20R steranes ratio, and more  
 697 elevated values of the  $C_{30}$   $\beta\alpha/\alpha\beta$  hopanes ratio in immature samples (Fig. 11). Additionally, the  
 698 Argillaceous Diatomites samples exhibits a lack of re-arranged steranes compared to the  
 699 overlying and underlying intervals (Fig. 11; Table 2).



700  
701 *Figure 9. n-alkane distribution in non-halite intervals.*

702 Two samples from each depositional unit (left and right columns) show the relative abundance of  
 703 pristane (Pr), phytane (Ph), and  $C_{16}$ - $C_{38}$   $n$ -alkanes. Note the odd-over-even carbon-number

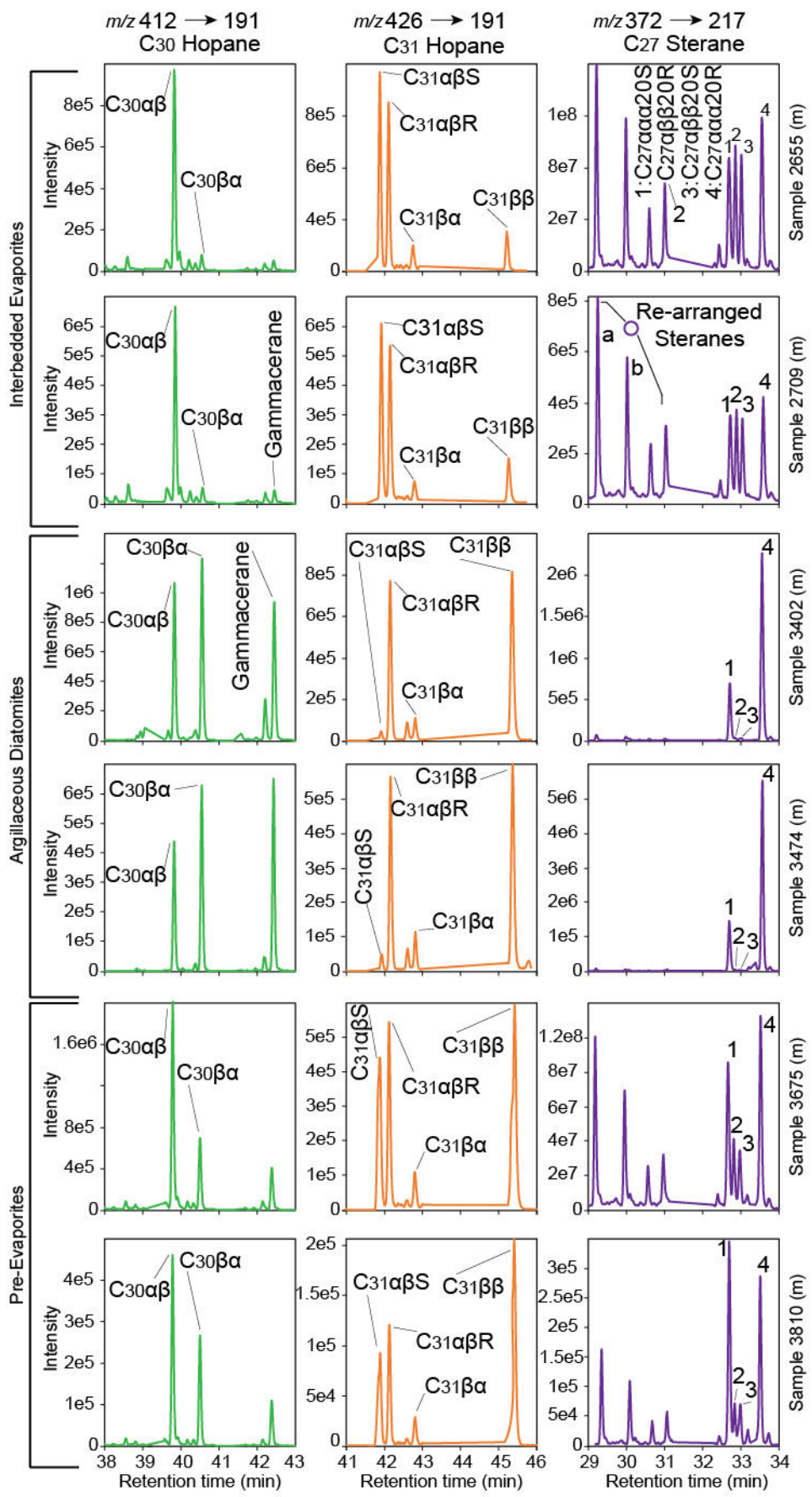
2073  
 2074  
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 2076 704 predominance of long-chain *n*-alkanes in the Argillaceous Diatomites (center) and ~~pre~~Pre-  
 2077 705 ~~evaporites~~Evaporites (lower) relative to the overlying Interbedded Evaporites. Also observe the  
 2078  
 2079 706 higher CPI, i.e., ~~the distribution~~the distribution of *n*-alkanes, in the Pre-Evaporites and  
 2080 707 Argillaceous Diatomites relative to the Interbedded Evaporites, and higher relative abundance of  
 2081  
 2082 708 medium-long chained compounds.  
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 2084 709



2100  
 2101 710  
 2102 711 *Figure 10. Pristane/phytane ratio to carbon preference index (CPI) plot.*

2103 712 Legend indicates the strata of plotted samples. Horizontal dashed line indicates the separation  
 2104  
 2105 713 of CPI values of marginal section across the MSC reported by Vasiliev et al. (2017). Note that  
 2106 714 the samples from the Interbedded Evaporites plot in the area of values measured in stage 3 of the  
 2107  
 2108 715 MSC (Vasiliev et al., 2017), while the lower samples from the Levant plot in the area of MSC  
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 2110 716 stage 1. Also note the separation in Pr/Ph values between the Interbedded Evaporites relative to  
 2111 717 the Pre-Evaporites and Argillaceous Diatomites.

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719 *Figure 11. Distribution of selected bacterial hopanes and algal steranes-.*

720 Two samples from each depositional unit (left and right columns) were investigated for the  
721 distribution of aliphatic hydrocarbons using selective reaction monitoring (SRM) analysis. Each  
722 sample (numbered on the right) includes a chromatogram for three given SRM transitions: 412  
723 → 191 (C<sub>30</sub> Hopane); 426 → 191 (C<sub>31</sub> Hopane); 372 → 217 (C<sub>27</sub> Sterane). The C<sub>27</sub> rearranged  
724 steranes are marked as (a) C<sub>27</sub>β $\alpha$  20S and (b) C<sub>27</sub>β $\alpha$  20R. High ratios of C<sub>31</sub>αβS/R hopanes and  
725 C<sub>27</sub>αααS/R steranes, along with low values of C<sub>31</sub>ββ/αβ and C<sub>30</sub>ββ/αβ hopane ratios, indicate a  
726 higher, yet mixed, maturity of the organic matter preserved in the Interbedded Evaporite shale  
727 samples compared to samples from the Pre-Evaporites and Argillaceous Diatomites. The  
728 underlying diatomite facies sediments are immature in nature, while the ~~pre~~Pre-evaporite  
729 Evaporite shale samples exhibit mixed signatures (e.g., high C<sub>31</sub>ββ/αβ hopanes and C<sub>27</sub> αααS/R  
730 steranes).

## 5. Discussion

### 5.1 Deep-sea halite depositional environment

The halite in the Dolphin well appears to be a pure, homogeneous layer, indicating a monotonous deposition of halite in the deep Levant Basin. Transmitted-light microscopy and SEM analysis of halite ~~grains-crystals~~ (<0.5 cm) throughout the section reveals no distinct sedimentological variations. XRD analysis also confirms a uniform, halite-dominated mineralogical composition (Fig. 4). ~~Swallowtail-twinnedGypsum microcrystals structures made out of calcium sulfates~~ were observed ~~on-within~~ several halite ~~grains-crystals~~ as seen in SEM-EDS (Fig. 8B-2), and elemental variations ~~s-~~Supporting shifts in the relative amounts of calcium sulfates deposited along the halite part of the section were apparent in XRF analysis (Fig. 8). However, we found no features similar to the lithological variations reported from the Realmonte salt mine (Lugli et al., 1999) or the intermediate depth halite of the Balearic Basin (~~site-Site~~ 134; Lugli et al., 2015), such as cumulates of halite plates settled out from a stratified water column, plate cumulates in a shallowing-upward sequence containing kainite layers, ~~nor~~ cumulates of skeletal hoppers with chevron overgrowths. The above conclusion might be biased due to the usage of well cutting, possibly not allowing to recognize these features. However, the mm-scale variations in the salt deposits shown by Lugli et al. (2015) should have been recognizable ~~on-in~~ the halite well cuttings. The lack of comparative features between the marginal halite and the Levant deep-basin halite is also evident when comparing the halite samples in the Dolphin well and halite deposits penetrated by DSDP drilling. There is a clear distinction between the featureless Dolphin halite and the halite interbedded with detrital sand and small anhydrite nodules recovered at DSDP ~~site-Site~~ 134 offshore Sardinia in the margins of the western Mediterranean (Hsü et al., 1973). The halite sampled in ~~site-Site~~ 134 is banded similarly to the

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754 Sicily halite reported by Lugli et al. (1999), with alternative cloudy and translucent beds.  
755 Similarly, the banded halite and polyhalite at DSDP Sites 374, 375 and 376 in the Eastern  
756 Mediterranean (Garrison et al., 1978) does not resemble the homogenous halite recovered in the  
757 Dolphin well. The homogeneous nature of the halite observed in the Dolphin well suggests  
758 continuous deep-sea deposition, in comparison to halite deposition in the shallower marginal  
759 basins.

760 Modern analogs for ancient deep-water halite depositional environments are scarce. An  
761 exception is the hypersaline Dead Sea, in which active precipitation of halite occurs within the  
762 deepest parts of the basin (Arnon et al., 2016; Sirota et al., 2016, 2017; Steinhorn, 1983; Stiller et  
763 al., 1997). The Dead Sea floor is divided into two principal environments: a deep, hypolimnetic  
764 lake floor, and a shallow, epilimnetic lake floor (Sirota et al., 2016, 2017). Halite continuously  
765 precipitates with seasonal variations influencing the type of halite formation on the deeper  
766 hypolimnetic lake floor. However, the shallow epilimnetic lake floor is also subject to seasonal  
767 variations, which produce annual unconformities related to halite deposition and dissolution. The  
768 epilimnion part of the lake is under-saturated during the summer and halite is dissolved, while  
769 winter is characterized by a heavily supersaturated water column and halite is crystallized (Sirota  
770 et al., 2016). Summer is associated with higher loss of water by evaporation from the lake  
771 compared to the winter. Sirota et al. (2016) argue that the seasonal halite deposition cycle in the  
772 Dead Sea epilimnion is controlled by the decrease in the saturation with increasing temperature,  
773 which overcomes the effect of enhanced summer evaporation. The hypolimnion is  
774 supersaturated and halite is crystallized throughout the year, with higher super-saturation and  
775 higher crystallization rates during winter. During summer, the undersaturated epilimnion  
776 dissolves halite, forming highly saturated dense solutions. These solutions flow to the

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777 hypolimnion, which becomes supersaturated and crystallizes halite. This process results in  
778 focusing of halite deposits in the deep hypolimnetic parts of the evaporitic sea, and thinning of  
779 the shallow epilimnetic deposits occurs (Sirota et al., 2016, 2017). The Dead Sea modern  
780 analogue provides a mechanism for explaining the great thickness of the deep Mediterranean  
781 MSC halite deposit. A similar model might have applied during the MSC, with halite dissolution  
782 in the marginal and intermediate basin evaporites, and focusing and thickening of halite  
783 deposition in the deeper parts of the basin, as also partly proposed by Roveri et al. (2014c).

## 784 **5.2 Stratigraphic markers in deep basin MSC deposits**

### 785 *5.2.1 Deep--basin diatomites as environmental and lithostratigraphic markers*

786 As no chronostratigraphic indicators were found in the studied section, we aim to use the  
787 litho-chemical analysis performed on the Dolphin well samples to identify lithostratigraphic and  
788 chemostratigraphic markers, that could-may serve as tie-points for establishing an age model for  
789 the deep basin MSC deposits (Fig. 12). In this context, the occurrence of diatomites within the  
790 Main Halite unit provides a primary observation. Diatomites are known to occur within Pre-  
791 Evaporite and PLG intervals in some of the marginal sections (Dela Pierre et al., 2014; Hilgen et  
792 al., 2007; Hilgen and Krijgsman, 1999; Krijgsman et al., 2001; Manzi et al., 2011; Roveri et al.,  
793 2014a), and more rarely within stage 3 Upper Gypsum deposits (e.g., Eraclea Monia section;  
794 Manzi et al., 2009). Diatom-rich aggregates within laminated layers, appearing as mudstone  
795 intervals interbedded within the PLG deposits of the Piedmont basin, were used by Dela Pierre et  
796 al. (2014) to establish the existence of normal--marine (not brackish or hypersaline) waters  
797 during deposition of non-evaporitic intervals during stage 1 of the MSC. Here we show that open  
798 --marine planktonic diatom taxa abundant in the Piedmont during the PLG (e.g., *Coscinodiscus*



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2467 803 *Figure 12. Astronomical age model and regional correlation of the Levant MSC*  
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2469 804 *The Levant interpreted lithology (left, from Fig. 2), biostratigraphic reference levels (PF –*  
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2471 805 *planktic foraminifera, below) and filtered well-log model (Figs. 5) determine a*  
2472 806 *cyclostratigraphic model, resulting with 33 cycles for the Levant MSC (shaded cycles). Note the*  
2473  
2474 807 *significantly lower cycle frequency in the ~~pre~~Pre-evaporites-Evaporites (2.3 m compared to 51 m*  
2475 808 *per-cycle), due to the much higher sedimentation rates in the evaporites interval. This*  
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2477 809 *cyclostratigraphic model is tuned to astronomic target curves (center) of ETP (blue; calculated*  
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2479 810 *as eccentricity (Ecc; red) + obliquity - precession ((1) Laskar et al., 2004)), 65°N summer*  
2480 811 *insolation (65°N SI; green) (Laskar et al., 2004), and marginal MSC deposits (right columns)*  
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2482 812 *based on astronomical calibrated ages and cycles identified across the Mediterranean ((1)*  
2483 813 *Laskar et al., 2004; (3) Roveri et al., 2014a, CIESM (2008); (4) Manzi et al., 2011; (5)*  
2484  
2485 814 *Krijgsman et al., 2001). The drop in sea level (SLG; sea level Gibraltar; (2) Ohneiser et al.*  
2486 815 *2015) corresponding to glacial peaks TG12-14 ( $\delta^{18}O$ ; as summarized in Roveri et al. (2014))*  
2487 816 *marks the top of the ~~main~~Main halite-Halite unit. The shift to post-evaporitic and clastic*  
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2489 817 *deposits of MSC stage 3 (Hilgen et al., 2007; Krijgsman et al., 2001; Laskar et al., 2004; Roveri*  
2490 818 *et al., 2014), through a stepwise deglaciation associated with sea-level rise (TG12-9), is here*  
2491 819 *astronomically tuned to enhanced clastic deposition in the Interbedded Evaporites and*  
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2493 820 *Argillaceous Evaporites units of the Levant.*  
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2498 822 To date, there are no reports of diatomites, or a diatom-rich assemblage in stages 2 of the MSC  
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2500 823 across the Mediterranean. Based on the taxonomic similarities between the deep and marginal  
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2502 824 planktonic marine diatom assemblages, we propose that the Levant diatomites constitute a  
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2504 825 temporal lithostratigraphic marker. If we follow the interpretation for the occurrence of planktic  
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2506 826 marine diatoms as indicators of partial connectivity with the Atlantic Ocean (Dela Pierre et al.,  
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2508 827 2014; Hüsing et al., 2009; Krijgsman et al., 2000), then their appearance interbedded within the  
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2510 828 halite in the Levant suggests that deposition of the halite layer occurred at a time of at least  
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2512 829 partial, periodic Atlantic connectivity, most likely during deposition of the PLG on the margins  
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2515 830 (5.97-5.6 Ma).

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2523 831 5.2.2 Allochthonous grains in the Interbedded Evaporites-*Argillaceous Evaporites* and stages 2-  
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2525 832 3 of the MSC  
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2528 833 The abrupt change that marks the onset of enhanced clastic input in the Interbedded  
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2530 834 Evaporites in the Levant Basin, together with endemic and reworked Eocene and Cretaceous  
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2532 835 foraminifera into the basin, matches other similar episodes reported from the MSC in the  
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2534 836 Mediterranean. Primarily, these are the clastic-rich deposits that result in the deposition of the  
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2536 837 Reworked Lower Gypsum (stage 2) and the Upper Gypsum and Lago-Mare deposits (stage 3) on  
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2538 838 the margins. These clastic deposits, including a similar abundance of minerals and reworked  
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2540 839 fauna, are not only reported from marginal sections (e.g., Lofi et al., 2011; Roveri et al., 2014),  
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2542 840 but also from cores of deeper parts of the basin (e.g., Sites 124 in the Western Med (Ryan et al.,  
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2544 841 2007), Site 654 ~~from-in~~ the Tyrrhenian Sea (Borsetti et al., 1990), and from Sites 374 and 376 in  
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2546 842 the Eastern Mediterranean (Cita et al., 2006; Hsü et al., 1978a, 1978b)).  
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2549 843 DSDP ~~sites~~ Sites 375 and 376 ~~on-at~~ the Florence Rise in the Eastern Mediterranean recovered  
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2551 844 nannofossil marlstones and dolomitic marlstones of latest Miocene age, overlying a gypsum with  
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2553 845 marlstone ~~evaporite~~-sequence; (Hsü, et al., 1978b). The gypsum with marlstone-~~evaporites~~,  
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2555 846 which are interpreted as deposits of a shallow subaqueous environment, are followed downwards  
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2557 847 by anhydrite and halite at Site 376 and are collectively recognized as the upper part of the  
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2559 848 Mediterranean evaporites. The interbedded gypsum contains reworked Cretaceous, Paleogene  
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2561 849 and lower/middle Miocene foraminifera and nannofossils, similar to the fauna identified in the  
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2563 850 clastic interval of the Interbedded Evaporites in the Dolphin well. The reworked fauna from ~~the~~  
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2565 851 Florence Rise are common to abundant in the bedded evaporites and rare to absent in the  
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2567 852 overlying Pliocene and underlying Tortonian and Serravallian (Hsü, et al., 1978b), indicating a  
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2569 853 distinctive phase of reworked sediments deposited within the Mediterranean basins. The  
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854 sedimentary response of the Interbedded Evaporites and Argillaceous Evaporites (Unitse 5 and 6,  
855 respectively; Gvirtzman et al., 2013; 2017; Manzi et al., 20018) in the Levant Dolphin and  
856 Leviathan-1 wells (from ~2270 m in the Dolphin well, Figs- 5, 12) resembles similar  
857 observations reported from shallower deposits in the Levant. For example, the Afiq Formation  
858 overlies the anhydrite-siliciclastic stage 2-RLG equivalent Mavqiim Formation (Druckman et al.,  
859 1995; Lugli et al., 2013) and was penetrated by the Or-South 1 well. It consists of Eocene-aged  
860 lithoclasts made of limestone, dolomite, and chert- and quartz--rich sand, overlying a  
861 conglomerate unit with brackish ostracods indicating a plausible correlation to the Lago-Mare  
862 stage (Derin, 2000). A fluvial or sabkha environment is attributed to this interval with subaerial  
863 exposure, supporting the idea of a considerable desiccation phase and subaerial exposure near the  
864 end of the MSC (Cita et al., 1978; Lofi et al., 2011; Madof et al., 2019; Ryan, 1978). Similar  
865 lithologies, including clasts of Eocene and Cretaceous age, were described from the marginal  
866 Nir-1 well in the Levant Basin above an erosion surface and beneath earliest Pliocene marls  
867 (Frey-Martinez et al., 2007). Similar clastic-conglomeratic and sandy lithologies are also  
868 reported from the Messinian Qawasim and Rosetta formations offshore Egypt (Leila et al.,  
869 2016); the latter correlates with the Afiq Formation in the Levant (Derin, 2000). Unfortunately,  
870 no samples are available from above the base of the Interbedded Evaporites in the deep Levant  
871 Basin to further confirm the lithological correlation between these sections and the deep Levant  
872 Basin. Correlation to more proximal sections and well-log interpretations indicate (~~see also~~  
873 ~~Gvirtzman et al., 2013; 2017; Manzi et al., 2018~~) that the overlying Argillaceous Evaporites  
874 mark a shift to more clastic and gypsum/anhydrite deposition (see also Gvirtzman et al., 2013;  
875 2017; Manzi et al., 2018).



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2635 876 We argue that the main change in the halite unit, characterized by mixing of clastic material  
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2637 877 into the deep-basin deposits at the base of the Interbedded Evaporites, correlates with the  
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2639 878 beginning of major sea-level drawdown and introduction of clastic material into the entire  
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2641 879 Mediterranean ~~basin~~Basin, from stage 2 of the MSC (5.61 Ma) through the Upper Gypsum and  
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2643 880 Lago Mare stages in the marginal basins (5.53-5.33 Ma; Argillaceous Evaporites in Fig. 12).  
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2645 881 During stage 2, sea-level drawdown eroded and redeposited the PLG gypsum into the marginal  
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2647 882 and intermediate parts of the basin (e.g., Lofi et al., 2011). The deep-basin expression ~~to~~of this  
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2649 883 regression might be the fine-grained clastics, including older reworked fauna, reaching the  
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2651 884 Mediterranean's depocenters. However, to further test this idea, and try to distinguish between  
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2653 885 stage 2 and 3 sediments, we compare biomarker distribution across the basin, and identify  
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2655 886 sedimentary cycles within the MSC of the Levant Basin.

### 2658 887 5.2.3 Basin-wide transport of organic matter

2661 888 The *n*-alkane distribution and CPI values of the Levant samples (Figs. 7 and 8; Table 1) are  
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2663 889 similar to some extent to those obtained from marginal and onshore MSC successions (Vasiliev  
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2665 890 et al., 2017), and provide further support for the introduction of reworked and mixed material  
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2667 891 into the Levant during the deposition of the Interbedded Evaporites. The *n*-alkane distribution of  
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2669 892 Mediterranean MSC samples covering the entire 640-kyr-long MSC interval shows distinct  
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2671 893 dissimilarities between several marginal to intermediate-depth sections (Vasiliev et al., 2017):  
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2673 894 ~~the~~The Monte Tondo (Primary Lower Gypsum; MSC stage 1), Realmonte salt mine (Halite and  
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2675 895 Re-sedimented Lower Gypsum; MSC stage 2), and Eraclea Minoa (Upper Gypsum/Lago Mare;  
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2677 896 MSC stage 3). The Delphine well *n*-alkane distribution shows a higher abundance of short-chain  
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2679 897 homologues in the Levant relative to marginal sections (Vasiliev et al., 2017), likely due to the  
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2681 898 lower relative input of terrestrial organic matter in more distal depositional settings. Several  
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2691 899 similarities exist between both data sets. Vasiliev et al. (2017) reported CPI values of 3.0-7.9 ~~in~~  
2692 ~~at~~ Monte Tondo (stage 1), and 1.7-3.7 ~~in~~ ~~at~~ Eraclea Minoa (stage 3; Fig. 10). While CPI values  
2693 900 ~~at~~ Monte Tondo (stage 1), and 1.7-3.7 ~~in~~ ~~at~~ Eraclea Minoa (stage 3; Fig. 10). While CPI values  
2694 901 were not reported from the halite samples of the Realmonte salt mine, Vasiliev et al. (2017) show  
2695 902 two different types of organic matter: 1) autochthonous sediment associated with gypsum or  
2696 903 halite deposited in place, and 2) allochthonous material associated with clastic sediments and  
2697 904 transport. Marked similarities in CPI values are therefore noted between the Levant and marginal  
2698 905 locations described by Vasiliev et al. (2017), with CPI values of 4.0-12.3 in the Main Halite  
2699 906 interval (indicating stage 1), and 1.9-2.9 in the Interbedded Evaporites interval (indicating stages  
2700 907 ~~2/-3~~) (Fig. 10).

2701  
2702 908 Vasiliev et al. (2017) also suggest that dissimilarities in the biomarker and isotopic  
2703 909 composition of stages 1 and 2, relative to stage 3 sediments, may be attributed to the outflow of  
2704 910 Black Sea (i.e., Paratethys) waters and their mixing into the Mediterranean, which paved the way  
2705 911 for Paratethyan ‘Lago-Mare’ type fauna. For instance, the distribution of *n*-alkanes and CPI  
2706 912 values in stage 3 ~~in~~ ~~at~~ Eraclea Minoa are more evenly distributed and lower, relative to those of  
2707 913 stage 1 (Fig. 3 in Vasiliev et al., 2017). We report a similar distinction in the *n*-alkane  
2708 914 distribution between the ~~upper Interbedded Evaporites~~ ~~clastic samples~~ and underlying sediments  
2709 915 (Table 1, Fig. 9). A much stronger odd-over-even predominance (i.e., higher CPI values) is  
2710 916 observed in the ~~Argillaceous~~ Diatomites, together with more elevated long-chain over short-  
2711 917 chain *n*-alkanes values (LCA/SCA; Table 1) and maturity parameters (Fig. 11; Table 2). This  
2712 918 indicates more immature source rocks with significantly different sources of the organic matter  
2713 919 in the Main Halite relative to the Interbedded Evaporites sediments (Bray and Evans, 1961;  
2714 920 Scalan and Smith, 1970).

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2746  
2747 921 The distribution of stereoisomers of algal steranes and bacterial hopanes (Fig. 11; Table 2)  
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2749 922 reflects the transformation, or stereoisomerization from biological epimers to a more stable  
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2752 923 geological molecular configuration as a consequence of thermal alteration (Peters, 1986; Peters  
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2754 924 et al., 2005, 1980). The evidence for enhanced thermal maturity in the Interbedded Evaporites  
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2756 925 relative to the underlying deposits (Fig. 11; Table 2) is counterintuitive, as thermal maturity  
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2758 926 should increase with depth (Peters et al., 2005, 1980). Furthermore, the Interbedded Evaporites  
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2760 927 exhibit mixed signals that include high values of the C<sub>31</sub> αβ S/R ratio (indicative of thermally  
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2762 928 mature organic matter) in addition to C<sub>31</sub> hopanes with the ββ biological configuration (indicative  
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2764 929 of immature organic matter) (Fig. 11; Table 2). This aspect further supports the occurrence of  
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2766 930 organic matter mixtures from differing ages and thermal histories, i.e., a higher proportion of  
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2768 931 allochthonous, thermally mature organic matter in the Interbedded Evaporites compared with the  
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2770 932 Main Halite and Pre-Evaporite samples. This interpretation is consistent with similar trends  
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2772 933 observed in early Paleogene (Sepúlveda et al., 2009) and Quaternary (Rashid and Grosjean,  
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2774 934 2006) studies. Such trends may reflect an intensification of the hydrological cycle, and thus  
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2776 935 enhanced precipitation, continental runoff, and the transport of re-worked, and pre-aged,  
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2778 936 continental or marginally-derived organic matter during the deposition of the Interbedded  
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2780 937 Evaporites. Another mechanism through which transport can occur is dense shelf-water  
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2782 938 cascading (DSWC) transport of sediment and associated organic matter from marginal settings to  
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2784 939 deep Mediterranean basins, as reported to occur in the Mediterranean today (Canals et al., 2009).  
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2786 940 The interpretation of transport in these intervals is consistent with the occurrence of clastic  
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2788 941 material, larger sub-rounded minerals, and re-worked Cretaceous and Eocene foraminifera within  
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2790 942 samples from the Interbedded Evaporites, which also supports the presence of reworked, older  
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2792 943 sediments. Both Cretaceous and Eocene organic-rich source rocks are known around the  
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2803 944 Mediterranean ~~basin~~-Basin (e.g., Almogi-Labin et al., 1993; Bayliss, 1973; Meilijson et al.,  
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2805 945 2014), and might represent sources of pre-aged weathered and transported organic matter,  
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2807 946 matching the apparent higher maturity measured from the organic--matter extract of the  
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2810 947 Interbedded Evaporites sediments.

2812 948 In summary, the similarities between our data and ~~that~~-of Vasiliev et al. (2017) suggest that  
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2814 949 organic geochemical analysis from the Dolphin well ~~can~~-might be used as regional  
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2816 950 chemostratigraphic markers to distinguish between Pre-Evaporites and Argillaceous Diatomites  
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2818 951 sediments, and the overlying Interbedded and Argillaceous Evaporites. A correlation between  
2819  
2820 952 MSC stage 3 and the ~~Interbedded Evaporites~~upper part of the MSC in the Levant Basin has been  
2821  
2822 953 previously proposed based on seismic interpretation and the sampling of shallower deposits  
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2824 954 (Druckman et al., 1995; Gvirtzman et al., 2017; Lugli et al., 2013). Here, we present evidence  
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2826 955 supporting the occurrence of stage 2 sea--level drawdown or stage 3 and ‘Lago-Mare’-type  
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2828 956 deposits in the deep domains of the Eastern Mediterranean. This includes increased supply of  
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2830 957 clastic material into the basin, reworked fauna, and chemostratigraphic markers (Figs- 3, 9 and  
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2832 958 10).

### 2836 959 **5.3 From cycles to astronomical tuning**

2838 960 Cyclostratigraphy and astronomical tuning of sediment sections, geochemical signals, and  
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2840 961 well--log responses have been extensively used for stratigraphic interpretations of MSC deposits  
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2842 962 across the Mediterranean (Dela Pierre et al., 2014; Hilgen et al., 2007, 2000, 1995; Hilgen and  
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2844 963 Krijgsman, 1999; Hüsing et al., 2010, 2009, Krijgsman et al., 2001, 1999, 1997; Lugli et al.,  
2845  
2846 964 2015; Manzi et al., 2015, 2013, 2012; Ochoa et al., 2015; Topper et al., 2014). The CIESM  
2847  
2848 965 stratigraphic model of the MSC has halite deposited in stage 2 of the MSC, during four  
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2850 966 insolation-precession cycles (e.g., Roveri et al., 2014a, with reference to Laskar et al., 2004; Fig.

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967 12). These are part of the 32 precession-controlled cycles (Laskar et al., 2004) identified across  
968 the Mediterranean, with a periodicity of about 20 kyr per cycle, amounting to the 640 kyr time  
969 frame of the MSC. Manzi et al. (2015) proposed to tune the high-reflectivity intervals in the  
970 seismic section of the Levant (interpreted as clastic units; Gvirtzman et al., 2013a) to summer  
971 insolation maxima, and the transparent intervals (interpreted as halite) to summer insolation  
972 minima, within these four insolation cycles. By contrast, the study of the Pre-Evaporites in the  
973 Dolphin well by Meilijson et al. (2018) and the results of this study suggest that salt formation  
974 began around 5.97 Ma, i.e., more or less synchronously with the marginal deposition of the PLG.  
975 According to this age-model, the evaporitic sequence in the Levant Basin (Fig. 12) was  
976 deposited between 5.97 and 5.33 Ma, corresponding to a time span of ~640 kyr rather than 50  
977 kyr, and encompassing 32 insolation cycles (Laskar et al., 2004). Our suggested scenario would  
978 imply an average cycle thickness of ~50 m, as the studied section is 1590 m thick.

979 Bandpass filtering of the Dolphin well logs resulted in the identification of 31 cycles, closely  
980 matching the 32 precession-controlled cycles (Laskar et al., 2004) in the interval between 5.97  
981 and 5.33 Ma. However, this age model includes several assumptions: (1) the evaporite record at  
982 the studied site is complete with no hiatus, (2) it is largely undisturbed by salt tectonics, and (3)  
983 ~~that~~ the sedimentation rate is approximately constant, with no significant changes between the  
984 halite-rich intervals and clastic-diatomitic intervals. The Dolphin record lacks  
985 chronostratigraphic tie points and contains intervals in which the log data are erratic (Fig-s 5,  
986 S2). Furthermore, the Dolphin well area appears deformed in the upper part of the section, and  
987 ~~missing~~ Unit 6 is missing (overlying the Interbedded Evaporites; Fig. 6). These sources of  
988 uncertainty suggest that the Dolphin well spectral analysis provides a first order approximation  
989 of the number of cycles, primarily across the lower part of the section. However, the large

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2914  
2915 990 number of cycles observed in the Main Halite interval, if assumed to reflect precessional cycles,  
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2917 991 suggests a longer period of deposition than ~50 kyr. The Leviathan-1 well is much less deformed  
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2919 992 (Fig-s 5, 6) and has a thick interval of Unit 6 (Gvirtzman et al., 2013; 2017), similar to the  
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2922 993 sequence at the Aphrodite well (Manzi et al., 2018). It also presents a good fit between the  
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2924 994 seismic and the RE well-log response, ~~The observed regularity which produced a filtered~~  
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2926 995 ~~cycles curve (Fig. 5), which the filtered cycles have reveals a good fit to with the well log target~~  
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2928 996 ~~curve. and a regularity that fits well the produced filtered cycles curve (Fig. 5).~~ We hypothesize  
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2930 997 that these cycles represent the 32 ~~insolation-precession~~ cycles identified in MSC sections across  
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2932 998 the Mediterranean. This would imply that the Main Halite interval in the lower part of the  
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2934 999 studied section is equivalent to stage 1 (PLG) in marginal sections, as also proposed by Meilijson  
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2936 et al. (2018).

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2939 1001 However, lacking chronostratigraphic tie points in the evaporitic section, an alternative  
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2941 1002 explanation for the cyclicity observed in the well logs of the halite and the seismic profiles  
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2943 1003 should be considered to reconcile the age model suggested by Manzi et al. (2018) for the Levant  
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2945 1004 Basin. In this model the FBI unit, ~~which represents the~~ uppermost ~~part of the p~~Pre-Eevaporites ~~in~~  
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2947 1005 ~~of the Aphrodite well,~~ corresponds to MSC stage 1 (the PLG; Manzi et al., 2018), ~~and while the~~  
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2949 1006 uppermost part of the section ~~correlates with~~corresponds to stage 3 (Unit 7; Gvirtzman et al.,  
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2951 1007 2017). Following this model, the ~33 cycles identified within the Leviathan-1 MSC section  
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2953 1008 (Figs- 5, 7) correspond to the ~50 kyr estimated for the duration of stage 2 of the MSC (Roveri et  
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2955 al., 2014), and have therefore a cycle duration of ca. 1560 years. If we take into account the  
2956 1009  
2957 likely different sedimentation rates of the Argillaceous Diatomites facies, this period could  
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2959 correspond to the period inferred for the Dansgaard-Oeschger events (1470 years), as observed  
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2961 during the second half of the last glacial (Schulz, 2002) (although see comments by Ditlevsen et  
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2971 1013 al. (2007) and Lohmann and Ditlevsen (2018) on the validity and interpretation of these cycles).  
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2973 1014 Alternatively, they could be explained by the Bond cycles, as observed for the North Atlantic  
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2975 1015 during the Holocene (1500 years; Bond et al., 2001). Another alternative are the periods of ca.  
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2977 1016 1000 years corresponding to the so-called Eddy cycle observed in the  $^{14}\text{C}$  record, which relate to  
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2979 1017 variations in solar activity (Steinilber et al., 2012). However, this last alternative is unlikely, ~~as~~  
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2981 1018 if the regular alternations in the halite would correspond to Eddy cycles, it implies that stage 2 of  
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2983 1019 the MSC ~~only~~ lasted only ~32 kyr. This means that the climax stage of the MSC cannot  
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2985 1020 encompass both glacial stages TG14 and 12 (Fig. 12), as is assumed in the CIESM model.  
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2988 1021 In the Realmonte salt mine in Sicily, 10-15 cm alternations in the salt have been interpreted as  
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2990 1022 annual cycles (Manzi et al. 2012). Such sedimentation rates of ca. 10 cm/yr would imply that the  
2991  
2992 1023 1,060 m thick Main Halite interval in the Levant could have been formed in a short time period  
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2994 1024 of 10,600 years, although average sedimentation rate may be lower in the Argillaceous  
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2996 1025 Diatomites. However, it is hard to reconcile such a short duration of deposition with the amounts  
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2998 1026 of halite required to build up the thickness of the Levant Basin halite layer.  
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3001 1027 In the absence of a simple explanation for the cyclicity observed in the Dolphin well, we now  
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3003 1028 consider its interpretation in relation to the different elements of the CIESM model for marginal  
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3005 1029 MSC deposits. The CIESM (2008) consensus stratigraphic model for the MSC is strongly based  
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3007 1030 on astronomical tuning of different MSC sections and includes the following division of the 32  
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3009 1031 orbital-related cycles identified during this time frame (Laskar et al., 2004): cycles 1-18 in stage  
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3011 1032 1 (PLG), 19-23 in stage 2 (RLG), 24-28 in stage 3.1 (lower part of Upper Gypsum), and 29-32 in  
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3013 1033 stage 3.2 (the Lago ~~-~~Mare). The correlation between the Levant MSC well ~~-~~log-based  
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3015 1034 astrochronology, the orbital target curves, and the chronology of shallow ~~to~~ marginal sections  
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3017 1035 (CIESM, 2008) of the MSC indicates the following: (1) the Main Halite interval (3759-2800 m  
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3027 1036 in the Leviathan-1 well) is bound between the Levant filtered cycles 1 through 19 (Fig. 12). A  
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3029 1037 comparison with the current MSC chronology (CIESM, 2008; Roveri et al., 2014a) shows a  
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3031 correlation with the number of cycles in the interval between 5.97 and 5.64 Ma from the base of  
3032 1038 the PLG (stage 1) to the base of the RLG (stage 2); (2) the Interbedded Evaporites interval  
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3034 1039 (2800-2320 m) is bound between the Levant filtered cycles 19 through 28 (Fig. 12), which  
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3036 1040 correlates to the number of cycles in in stage 2 (the RLG; 5.64-5.53-55 Ma; cycles 19-23), with  
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3038 1041 and its top ~~is~~ known as the ‘top salt’ horizon, and the lower part of stage 3 (stage 3.1 the Upper  
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3040 1042 Gypsum who’s base is at 5.42 Ma). Thus, the lower part of the Interbedded Evaporites is also  
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3042 1043 equivalent to stage 2 halite deposits recognized in intermediate basins, such as the Realmonte  
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3044 1044 salt mine in Sicily; (3) at the upper part of the ~~section--Interbedded Evaporite and~~ the  
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3046 1045 Argillaceous Evaporites interval is-are equivalent to ~~the-continuation-of~~ stage 3 of the MSC  
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3048 1046 (2320-2090 m; Fig. 12), ending with the clastic Lago-Mare interval.  
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3051 1048 Following the suggestion of Meilijson et al. (2018) ~~of-for~~ an early onset of halite deposition in  
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3053 1049 the deep Mediterranean basins, similar claims were made by García-Veigas et al. (2018) based  
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3055 1050 on sulfur stable-~~isotopes~~ analysis of marginal and intermediate basin gypsum deposits. They  
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3057 1051 hypothesize that the deep-~~basin~~ halite deposits are not equivalent to one phase of deposition  
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3059 1052 during stage 2 of the MSC, but rather comprise two to three phases of halite deposition,  
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3061 1053 beginning with halite deposition during stage 1 of the MSC. Our astronomical tuning agrees with  
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3063 1054 this idea by positioning the boundary between stage 1 and 2 of the MSC (2762 m in the Dolphin  
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3065 1055 well, 2800 m in Leviathan-1) at the top of the Main Halite interval. Consequently, we propose  
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3067 1056 that the Main Halite is equivalent to stage 1 gypsum deposits of the PLG, as indicated  
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3069 1057 independently by the diatomite facies. The increase in clastic and re-worked faunal material into  
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3071 1058 the basin fits well with our astrochronology, placing the Interbedded Evaporites within the time  
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3083 059 period of the Re-worked Lower Gypsum (stage 2 of the MSC). Sea-level drawdown promoted  
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3085 060 the scraping of the shelf, re-shaping of drainage and transport systems across the basin, and re-  
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3087 061 depositing of vast amounts of eroded gypsum-sediment into the intermediate basins. It also  
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3090 062 delivered vast amounts of fine-grained material to the deep basins, as observed in the  
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3092 1063 Interbedded Evaporites in the Levant Basin. Lastly, the identification of the *Discoaster*  
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3094 1064 *quinqueramus* in Unit 5 (the Interbedded Evaporites) by Manzi et al. (2018) supports this  
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3096 065 conclusion, as this species went extinct towards the end of stage 2.  
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#### 3099 1066 **5.4 Implications of a new MSC chronology in the Mediterranean**

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3101 1067 While not conclusive, the integration of our different stratigraphic proxies supports an early  
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3103 068 and long-lasting deposition of deep-basin halite. The direct implication of this age-model is that  
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3105 069 halite was deposited in the deep Eastern Mediterranean when sea level was high and partial,  
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3107 070 episodic connection with the Atlantic still prevailed (Dela Pierre et al., 2014; Flecker and Ellam,  
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3109 1071 2006; Krijgsman et al., 2002; Roveri et al., 2014b), synchronously with gypsum deposition along  
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3111 072 the Mediterranean margins and intermediate basins (Ochoa et al., 2015). Our results do not  
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3113 1073 exclude an evaporative drawdown (e.g., Lofi, et al., 2011; Rouchy and Caruso, 2006; Ryan,  
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3115 1074 2008) and lower sea level at the acme of the MSC during stage 2 (Ohneiser et al., 2015). The  
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3117 1075 lack of sedimentological features within the monotonously clean halite, and our interpretation of  
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3119 076 long-lasting deep-water evaporite depositional settings, indicate that salt must have started to  
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3121 077 precipitate within a deep-basin-deep-water environment, and not in shallow-waters. We  
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3123 078 propose that sea-level drawdown actually prompted enhanced transport of clastic sediments into  
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3125 079 the deep basin resulting with-in the deposition of the Interbedded Evaporites unit, analog to the  
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3127 080 marginal deposition of the RLG. Studies of strontium isotopes from the Lower Evaporites (PLG,  
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3129 081 MSC stage 1) consistently report isotopic values close to those characteristic of the global oceans  
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1082 (Flecker and Ellam, 2006; Roveri et al., 2014b), and do not support an early desiccation model  
1083 (Cita, 1976; Hsü, 1973). While advocating a different chronological model, our study is  
1084 consistent with these interpretations and shows that halite deposition started during a time when  
1085 Atlantic inflow was still evident.

1086 A coeval initiation of basinal halite and marginal gypsum precipitation calls for a reevaluation  
1087 of previous models for MSC development, as well as its effect on global ocean salinity and  
1088 climate. We refer to the timing and persistence of halite deposition (which may have been an  
1089 order of magnitude larger than previously thought), and also to the substantially lower rates of  
1090 deposition of the deep-basin salt unit, from a previous assumption of 3,000 cm/kyr (according to  
1091 CIESM chronology) to 250 cm/kyr as deduced ~~by~~ from our new age model. Although this  
1092 assumes continuous precipitation and no dissolution, which we consider unlikely if the water is  
1093 being relatively refreshed with additional seawater throughout deposition. The Levant  
1094 chronostratigraphic model suggests that steady state of halite deposition was achieved and  
1095 maintained earlier in the MSC than previously thought. Both halite and gypsum could have been  
1096 precipitated ~~be~~-synchronously ~~precipitated~~, with their partitioning possibly governed by their  
1097 different solubility product constants ( $K_{sp}$ ) and ion availability. Furthermore, if we allow for an  
1098 order of magnitude change in the time scale of halite precipitation, then the required  
1099 sedimentation flux that removes sodium and chlorine from seawater is reduced. This exercise  
1100 substantially reduces the total sea-level drawdown (Ryan, 2008) required to explain the  
1101 deposition of a ~2 km-thick salt deposit. A further possible mechanism to explain the  
1102 synchronous deposition of gypsum and halite in marginal and deeper parts of the basin,  
1103 respectively, includes density stratification and down-shelf cascading of brines (Roveri et al.,  
1104 2014c; Sirota et al., 2017). While salt-saturated shallow waters seem to have reached gypsum

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1105 saturation values, brine formation might have continuously flowed down-shelf, in a similar  
1106 manner as dense shelf-water cascading (DSWC) is observed today around the Mediterranean  
1107 Basin (Canals et al., 2009, 2006). DSWC is associated with mass-transport complexes and  
1108 submarine channels, and has a significant impact on the sediment and organic-matter supply  
1109 from continental and shallow-marine settings to deep-sea ecosystems. Mass-balance calculations  
1110 suggest that the input of dissolved organic carbon and suspended particulate organic carbon from  
1111 ocean margins to the open ocean interior may be more than an order of magnitude greater than  
1112 direct inputs of organic carbon produced near the ocean surface today (Bauer and Druffel, 1998).  
1113 Similarly, highly saturated waters produced in an evaporitic Mediterranean may have produced  
1114 vast quantities of brine accumulating in the deep depocenters. Brine formation may have been at  
1115 least partly controlled by precession-induced increases in river runoff (Marzocchi et al., 2015),  
1116 and potentially by surface inflow from the Paratethys (Karakitsios et al., 2017; Krijgsman et al.,  
1117 2010). Salinity stratification is supported by geochemical evidence for the occurrence of low-  
1118 salinity surface waters overlying deep brines at gypsum and halite saturation (Christeleit et al.,  
1119 2015), as well as by the presence of brackish-water faunas of Paratethyan origin in the Lago-  
1120 Mare phase (Stoica et al., 2016). Our data, including high concentrations of long-chain *n*-alkanes  
1121 (Table 1) and high LCA/SCA values (Table 1), also support the occurrence of increased river  
1122 runoff into the basin during the deposition of the Interbedded Evaporites.

1123 Our interpretation of a deep-basin-deep-water model and early onset of halite, rejuvenates  
1124 an idea that has been a focus of debate in the past (e.g., Garcia-Castellanos and Villaseñor, 2011;  
1125 Lofi et al., 2011; Ryan, 2008; Schmalz, 1969). Simon and Meijer (2017) used a box-model setup  
1126 to model the MSC events forced by Atlantic exchange and evaporative loss. This model  
1127 demonstrated that a significantly stratified Mediterranean water column could have been

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1128 established early in the crisis, while the duration of halite deposition must have taken longer than  
1129 currently considered in the MSC stratigraphic consensus model. The synchronous formation of  
1130 gypsum and halite in proximal and distal basins, respectively, could have occurred at different  
1131 levels within the basin, with lower rates of halite sedimentation than previously thought. Our  
1132 data supports the model by Simon and Meijer (2017) and calls to reevaluate Mediterranean MSC  
1133 sections, while considering a possible early deposition of halite.

1134 Sea-level drop during stage 2 of the MSC may have added more proximal basins to the  
1135 regional deep-sea deposition of halite, which might explain why those intermediate-basin halite  
1136 deposits correlate to the stage 2 RLG. Such a mechanism can explain the existence of marginal  
1137 or intermediate-depth basins with relatively thin halite deposits, which only correlate with the  
1138 Interbedded evaporites-Evaporites interval in the Levant (Fig. 12), in which halite is still the  
1139 dominant lithology. For example, the marginal Realmonte salt mine has a ~600 m thick halite  
1140 sequence (Lugli et al., 1999; Roveri et al., 2014a) compared with the thick (>2 km) halite  
1141 deposits in deep Mediterranean basins. In a similar manner, recent studies from the Dead Sea  
1142 demonstrate downslope-flowing brines, in which the deep basinal areas accumulate the most  
1143 brine and the marginal areas are influenced by fresher waters and hence subject to more  
1144 dissolution (Sirota et al., 2016).

1145 Being one of the largest and youngest salt giants formation episodes in Earth's history, the  
1146 MSC is repeatedly used as a cornerstone for explaining evaporite deposition. Our new model,  
1147 which includes the synchronous deposition of sulfates in the margins of the basin and halite at its  
1148 center, calls for a re-evaluation of the mechanisms governing evaporite deposition in other salt-  
1149 giant deposits in the geologic record. For example, in the Permian Zechstein-, similar to the  
1150 Mediterranean, sulfates appear to have been limited to the margins while halite was deposited in

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151 the deeper parts of the basin (Richter-Bernburg, 1985). This is also the case for the Permian ~~aged~~  
152 Delaware Basin in Texas and New Mexico, where clear inter-fingering between sulfates and  
153 halite are observed as brine concentrations oscillate (Anderson and Dean, 1995).

1154 The alternating clastic and evaporitic sediments of the Interbedded Evaporites (Unit 5;  
1155 Gvirtzman et al., 2013; 2017) include cycles 19-28, matching in its lower part the time frame of  
1156 MSC stage 2, the RLG. Isolation from the Atlantic and significant sea-level drawdown ~~is-are~~  
1157 proposed as the formation mechanism for both the onshore deep subaerial canyons and offshore  
1158 erosion surfaces across the Mediterranean (Lofi et al., 2011; Ryan, 1976; Ryan and Cita, 1978).  
1159 Different models were proposed to explain the mechanisms behind erosion, transport, and re-  
1160 deposition, such as early subaqueous large-scale mass-wasting processes occurring at the  
1161 beginning of the MSC drawdown, subaerial rivers down-cutting by retrogressive action to adjust  
1162 for their new base level, or marine abrasion as possible agent for late erosion (Lofi et al., 2011  
1163 and references therein). Regardless of the mechanism, clastic geometries are clear in MSC  
1164 seismic sections and are partly controlled by local factors such as the dimension of the drainage  
1165 basin, resulting in major differences between the Messinian sedimentary successions in the  
1166 different areas of the Mediterranean. The whereabouts of the massive products of ~~this-these~~  
1167 basin-wide erosional processes ~~es~~ has been one of the MSC's enigmas (Ryan, 1976; Ryan and Cita,  
1168 1978; Lofi et al., 2011). The seismic facies defined as the Complex Unit (CU; Lofi et al., 2011)  
1169 in the Western Mediterranean is either chaotic or roughly bedded, and is believed to account for  
1170 some of the waste products. CU deposits are absent on the margin shelves, rarely observed on the  
1171 upper slopes, and mainly ~~recovered-observed at-along~~ the ~~margin-footbase of the slopes~~, either as  
1172 fan-shaped deposits at the Messinian river mouths or as poorly organized bodies elsewhere. This

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3362  
3363 173 unit ~~makes marks~~ the transition between the eroded slopes and deep-basin deposits (Lofi et al.,  
3364 1174 2011). The CU is positioned above or parallel to the Mobile Unit (the halite).  
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3367 In summary, stage 2 of the MSC is characterized by massive sediment displacement, for  
3368 1175 which only a portion is accounted for. We propose that the Interbedded Evaporites (Unit 5;  
3369 1176 Gvirtzman et al., 2017) are part of this high-energy system and that the interbedding of clastics  
3370 1177 represents the deep-basin depocenters for the fine grained material at the distal part of the  
3371 1178 drainage system. These precession~~al~~-controlled clastic incursions ~~were displaced~~reached into an  
3372 1179 evaporitic system, which in the deep basins has been depositing halite for ~360 kyr during stage  
3373 1180 1 of the MSC. We argue that this idea could not be examined before due to lack of a sedimentary  
3374 1181 record from the deep basin and the difficulty of correlating marginal and deep-basin units based  
3375 1182 on seismo-stratigraphy. The call for caution regarding the interpretation of MSC-related  
3376 1183 offshore data was recently presented by Roveri et al. (2019). They pointed out that MSC units  
3377 1184 having with different age, nature and depositional settings, may show similar seismic facies and  
3378 1185 geometries. On the other hand, the same units may appear as belonging to different seismic  
3379 1186 facies, either with parallel and high-amplitude reflections or even transparent or chaotic  
3380 1187 reflectivity due to seismic interference patterns related to the dominant frequency. We therefore  
3381 1188 argue against lumping the different facies of the Interbedded Evaporites into a unified deep-basin  
3382 1189 halite deposit, disregarding its clastic nature, as done in past interpretations of the Levant  
3383 1190 Basin MSC section (e.g., Manzi et al., 2018). Here we offer new sedimentological analysis of the  
3384 1191 non-evaporitic facies, interpreted in the past as clastic deposits through seismic and well-log  
3385 1192 interpretation (e.g., Feng et al., 2016). We argue that two different ‘non-halite’ deposits exist in  
3386 1193 the Levant deep MSC deposits: 1) ~~The~~the mostly biogenic remains of diatoms (the Argillaceous  
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195 Diatomites) within the stage 1 Main Halite interval, and 2) ~~The~~the clastic and reworked deposits  
1196 of the Interbedded Evaporites/Argillaceous Evaporites belonging to stage 2 and 3 of the MSC.  
1197 Stage 3 of the MSC is generally characterized by reworking of shelf sediments and their  
1198 occasional influx into the basin during renewed gypsum deposition. We position the base of  
1199 stage 3 within the Interbedded Evaporites- at cycle 23 (Figs: 5, 6, 712), pointing to a much  
1200 thicker stage 3 section in the Levant ~~then~~than in the model of Gvirtzman et al. (2017), Manzi et  
1201 al. (2018), or Madof et al. (2019). Relying on the CIESM (2008) stratigraphic model, these  
1202 separate studies position the halite into stage 2, and continue stage 2 until almost the top of the  
1203 Levant MSC section. They position stage 3 at the topmost part of the section, represented only  
1204 by Unit 7 - a thin anhydrite and shale unit (~~as~~ interpreted by well-log data in the deep basin as  
1205 no study has recovered samples from this interval thus far). These studies mainly differ in their  
1206 interpretation of the stage 3 depositional environment, namely subaerial (Madof et al., 2019) or  
1207 subaqueous (Gvirtzman et al., 2017) dissolution/ and truncation. According to our depositional  
1208 model (Fig. 12), Unit 6 belongs to stage 3 of the MSC (the Upper Gypsum and Lago Mare;  
1209 CIESM, 2008), and the IMTS (Gvirtzman et al., 2017) or IES (Madof et al., 2019)  
1210 unconformities in the Levant represent the transition between stage 3.1 (Upper Gypsum) and 3.2  
1211 (Lago Mare) of the MSC. The latter stage (3.2) was attributed to Unit 7 and perhaps also to parts  
1212 of the overlying brackish Afik Formation (Druckman et al., 1995) by Gvirtzman et al.  
1213 (~~2018~~2017). The introduction of Paratethyan waters and sediment, termed Lago Mare deposits  
1214 along the Paratethyan side of the Mediterranean, is also likely to have reached the deep basins.  
1215 However, while those might have reached the Levant Basin, different local drainage systems are  
1216 most likely the sources for the MSC stage 3 transported sediments in the Levant area. A local  
1217 source for transported sediments is the Nile drainage and fan systems, identified as reaching

3473  
3474  
3475 218 further north-west, beyond the Dolphin and Leviathan wells, towards the Eratosthenes Seamount  
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3477 219 offshore Cyprus (Hawie et al., [2013b](#)[2013a](#), [2013a](#)[2013b](#)). In addition, local drainage systems  
3478  
3479 220 that may have supplied the transported sediments ~~observed~~ include the Afiq and Ashdod canyons  
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3481 221 (Bertoni and Cartwright, 2007; Druckman et al., 1995), and the southern Turkey and western  
3482  
3483 222 Syria drainage systems proposed by Madof et al. (2019).  
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## 3486 1223 **6. Conclusions**

3489 1224 Over the past 50 years, models explaining the formation of offshore MSC deposits have  
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3491 1225 remained hypothetical in the absence of a complete sedimentary record of the deep  
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3493 226 Mediterranean ~~basin~~[Basin](#). The current study presents ~~results~~[results](#) from the offshore Dolphin  
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3495 227 and Leviathan-1 wells, which penetrated MSC evaporites ~~at from~~ 2,025 to 3,616 ~~m.b.s.lm~~, and  
3496  
3497 ~~from~~ 2,090 to 3,759 ~~m.b.s.lm~~, respectively. Our results challenge some of the current models for  
3498 228  
3499 229 the MSC, regarding the synchronicity or diachronism of evaporite deposits across the  
3500  
3501 230 Mediterranean ~~basin~~[Basin](#), their composition, and controlling factors. A longer duration for  
3502  
3503 231 halite deposition [than previously assumed](#) impacts our understanding of the biochemical and  
3504  
3505 1232 spatial constraints of this time period. While similar ideas have been previously raised (e.g., Van  
3506  
3507 1233 Couvering et al., 1976; Govers, 2009; Hardie and Lowenstein, 2004; Meilijson et al., 2018;  
3508  
3509 1234 Ryan, 2011; Simon and Meijer, 2017), we provide the first report on sedimentological data from  
3510  
3511 1235 the deep basin MSC halite deposits supporting the scenario of long-lasting salt deposition. We  
3512  
3513 1236 call for a re-evaluation of models based on a ~50 kyr-long deposition of halite in the deep basins.  
3514  
3515 1237 However, samples from the upper part of the deep MSC deposits in the Eastern Mediterranean  
3516  
3517 238 are not ~~currently~~[yet](#) available, while the existing sedimentary record drilled by the industry  
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3519 1239 consists of well cuttings and not a continues core. The complexity revealed by this study makes a  
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1240 strong case for future scientific drilling efforts that can retrieve cores from different parts of the  
1241 deep-basin halite deposits of the Mediterranean.

1242 This study aimed at addressing the composition and key stratigraphic questions regarding the  
1243 timing and correlation of MSC events in the deep Mediterranean. Our main findings can be  
1244 summarized as follows:

1. The formation of thick halite deposits in the Levant Basin occurred in a deep-basin deep-water environment that began earlier than previously thought, during the PLG phase of gypsum precipitation ~~on~~in the marginal ~~basins~~basins. This implies that a shallow desiccated scenario is not necessarily required to generate halite ~~precipitation~~precipitation during the MSC. The presence of well-preserved marine planktonic diatoms within the massive halite deposits strongly supports a periodic connectivity between the Atlantic and the Eastern Mediterranean during halite deposition.
2. The exact timing for the end of deep ~~basin~~ basin halite precipitation is still unclear. Well ~~log~~ log interpretation, cyclostratigraphy, and the astronomical tuning model presented here suggest that halite deposition continued at least until 5.45 Ma, and interbedded clastic material and evaporite~~s~~s (probably mainly gypsum/anhydrite) persisted until ca. 5.33 Ma.
3. The transition into the Interbedded Evaporites interval at 2,560 m at Dolphin and 2,800 m at Leviathan-1 marks a major shift in the mode of deposition. An increase in basin-ward transport of sediments is indicated by the high abundance of larger sub-rounded clastic grains such as quartz and plagioclase ~~minerals~~minerals, clay, micrite, and reworked Cretaceous ~~and to~~and to Eocene benthic and planktic foraminifera. Variable ~~ranges of organic matter~~ranges of organic matter thermal maturity indices also point to mixed sources of organic matter sediment. In general, biomarker indices in the Interbedded Evaporites resemble those measured

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3588 1263 elsewhere in the Mediterranean Basin from strata with transported material and mixed  
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3590 1264 sources. The transition from the Main Halite to the Interbedded Evaporites at 2,560 m  
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3592 1265 most likely represents the transition between stage 1 and 2 of the MSC. The ~~massive~~-large  
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3594 1266 amounts of clastic sediments in the Interbedded Evaporites are possibly an answer to one  
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3596 1267 of the MSC enigmas, regarding the location of the transported material related to the sea-  
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3598 1268 level drawdown of stage 2 and the ~~closer~~-interruption of the connection with of the Atlantic  
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3600 1269 Ocean.

- 3601  
3602 1270 4. During the MSC, high sea level and partial connectivity with the global oceans promoted  
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3604 1271 the deposition of deep-basin deep-water halite, while sea-level drawdown promoted  
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3606 1272 deposition of reworked and transported material from the margins into deep  
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3609 1273 Mediterranean basins.

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1288 **References**

1289 Alinat, J., Cousteau, J., 1962. Accidents de terrain en mer de Ligurie. *Océanographie géologique*  
1290 et géophysique de la Méditerranée occidentale, 121. Centre national de la recherche  
1291 scientifique, Paris.

1292 Almogi-Labin, A., Bein, A., Sass, E., 1993. Late Cretaceous upwelling system along the  
1293 Southern Tethys Margin (Israel): Interrelationship between productivity, bottom water  
1294 environments, and organic matter preservation. *Paleoceanography* 8, 671–690.  
1295 doi:10.1029/93PA02197

1296 Anderson, R.Y., Dean, W.E., 1995. Filling the Delaware Basin: Hydrologic and Climatic  
1297 Controls on the Upper Permian Castile Formation Varved Evaporite, in: Scholle, P.A.,  
1298 Peryt, T.M., Ulmer-Scholle, D.S. (Eds.), *The Permian of Northern Pangea: Volume 2:*  
1299 *Sedimentary Basins and Economic Resources*. Springer Berlin Heidelberg, Berlin,  
1300 Heidelberg, pp. 61–78. doi:10.1007/978-3-642-78590-0\_4

1301 Arnon, A., Selker, J.S., Lensky, N.G., 2016. Thermohaline stratification and double diffusion  
1302 diapycnal fluxes in the hypersaline Dead Sea. *Limnol. Oceanogr.* 61, 1214–1231.  
1303 doi:10.1002/lno.10285

1304 Bauer, J.E., Druffel, E.R.M., 1998. Ocean margins as a significant source of organic matter to  
1305 the deep open ocean. *Nature* 392, 20–23. doi:10.1038/33122

1306 Bayliss, D.D., 1973. *Micropalaeontology of sections Cenomanian to Middle Eocene West Bank*  
1307 *of Jordan*. London.

1308 Bellaiche, G., Genesseeux, M., Mauffret, A., Rehault, J.P., 1974. Prélèvements systématique et  
1309 caractérisation des réflecteurs acoustiques: nouvelle étape dans la compréhension de la  
1310 géologie de la Méditerranée occidentale. *Marine Geology* 16, M47–M56.

3753  
3754  
3755 1311 Berggren, W.A., Kennett, J.P., Srinivasan, M.S., 2006. Neogene Planktonic Foraminifera: A  
3756  
3757 Phylogenetic Atlas. *Micropaleontology*. doi:10.2307/1485586  
3758 1312  
3759  
3760 1313 Bertoni, C., Cartwright, J.A., 2007. Major erosion at the end of the Messinian Salinity Crisis:  
3761  
3762 Evidence from the Levant Basin, Eastern Mediterranean. *Basin Res.* 19, 1–18.  
3763  
3764 1315 doi:10.1111/j.1365-2117.2006.00309.x.  
3765  
3766 1316 Bertoni, C., Cartwright, J.A., 2006. Controls on the basinwide architecture of late Miocene  
3767  
3768 (Messinian) evaporites on the Levant margin (Eastern Mediterranean). *Sediment. Geol.*  
3769 1317  
3770 188–189, 93–114. doi:10.1016/j.sedgeo.2006.03.019.  
3771 1318  
3772  
3773 1319 Biehl, B.C., Reuning, L., Strozyk, F., Kukla, P.A., 2014. Origin and deformation of intra-salt  
3774  
3775 sulphate layers: An example from the Dutch Zechstein (Late Permian). *Int. J. Earth Sci.*  
3776 1320  
3777 103, 697–712. doi:10.1007/s00531-014-0999-4  
3778 1321  
3779  
3780 1322 Blanc, P., 2000. Of sills and straits : a quantitative assessment of the Messinian Salinity Crisis.  
3781  
3782 *Deep. Res. I* 47, 1429–1460.  
3783  
3784 1324 Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-  
3785  
3786 1325 Bond, R., Hajdas, I., Bonani, G., 2001. Persistent Solar Influence on North Atlantic Climate  
3787  
3788 1326 During the Holocene. *Science* (80-. ). 294, 2130–2136.  
3789  
3790  
3791 1327 Borsetti, A. M., Curzi, P. V., Landuzzi, V., Mutti, M., Ricci Lucchi, F., Sartori, R., Tomadin, L.,  
3792  
3793 1328 Zuffa, G.G., 1990. Messinian and pre-Messinian sediments from ODP leg 107 Sites 652 and  
3794  
3795 1329 654 in the Tyrrhenian Sea: sedimentological and petrographic study and possible  
3796  
3797 1330 comparisons with Italian sequences, in: Kastens, K. A., Mascle, J., et al. (Ed.), *Proc. Ocean*  
3798  
3799 1331 *Drill. Program, 107 Sci. Results* 107, 169–186. doi:10.2973/odp.proc.sr.107.161.1990.  
3800  
3801  
3802 1332 Bourcart, J., Boillot, G., Cousteau, J.Y., Gennesseaux, M., Klimek, C., 1958. Les sediments  
3803  
3804  
3805  
3806  
3807  
3808

3809  
3810  
3811 1333        profonds au large de la cote nicoise. Comptes Rendus de l'Academie des Sciences Paris  
3812  
3813 1334        147, 116.  
3814  
3815  
3816 1335    Bray, E.E., Evans, E.D., 1961. Distribution of n-paraffins as a clue to recognition of source beds.  
3817  
3818 1336        Geochim. Cosmochim. Acta 22, 2–15. doi:10.1016/0016-7037(61)90069-2  
3819  
3820 1337    Buchbinder, B., Zilberman, E., 1997. Sequence stratigraphy of Miocene-Pliocene carbonate-  
3821  
3822 1338        siliciclastic shelf deposits in the eastern Mediterranean margin (Israel): effects of eustasy  
3823  
3824 1339        and tectonics. Sediment. Geol. 112, 7–32.  
3825  
3826 1340    Camerlenghi, A., Aosis, V., Lofi, J., Hübscher, C, deLange, G., Flecker, R., Garcia-Castellanos,  
3827  
3828 1341        D., Gorini, C., Krijgsman, W., Lugli, S., Makovsky, Y., Manzi, V., McGenity, T., Pan, N.,  
3829  
3830 1342        2014. Uncovering a Salt Giant. Deep-Sea Record of Mediterranean Messinian Events  
3831  
3832 1343        (DREAM) multi-phase drilling project, in: EGU. Vienna, p. 1.  
3833  
3834 1344    Canals, M., Danovaro, R., Heussner, S., Lykousis, V., Puig, P., Trincardi, F., Calafat, A.,  
3835  
3836 1345        Durrieu de Madron, X., Palanques, A., 2009. Cascades in Mediterranean Submarine Grand  
3837  
3838 1346        Canyons. Oceanography 22, 26–43. doi:10.5670/oceanog.2009.03  
3839  
3840 1347    Canals, M., Puig, P., de Madron, X.D., Heussner, S., Palanques, A., Fabres, J., 2006. Flushing  
3841  
3842 1348        submarine canyons. Nature 444, 354–357. doi:10.1038/nature05271  
3843  
3844 1349    Christeleit, E.C., Brandon, M.T., Zhuang, G., 2015. Evidence for deep-water deposition of  
3845  
3846 1350        abyssal Mediterranean evaporites during the Messinian salinity crisis. Earth Planet. Sci.  
3847  
3848 1351        Lett. 427, 226–235. doi:10.1016/j.epsl.2015.06.060  
3849  
3850 1352    CIESM, 2008. The Messinian Salinity Crisis from mega-deposits to microbiology - A consensus  
3851  
3852 1353        report. N° 33. CIESM Work. Monogr. 7–10.  
3853  
3854 1354    Cita, M.B., 1976. Biodynamic effects of the messinian salinity crisis on the evolution of  
3855  
3856 1355        planktonic foraminifera in the mediterranean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 20,  
3857  
3858  
3859  
3860  
3861  
3862  
3863  
3864

3865  
3866  
3867 1356 23–42. doi:10.1016/0031-0182(76)90023-7  
3868  
3869 1357 Cita, M.B., Ryan, W.B.F., Kidd, R.B., 1978. Sedimentation rates in neogene deep-sea sediments  
3870  
3871 from the mediterranean and geodynamic implications of their changes, in: Initial Reports of  
3872 1358 the Deep Sea Drilling Project. pp. 991–1002.  
3873  
3874 1359  
3875  
3876 1360 Cita, M.B., Santambrogio, S., Melillo, B., Rogate, F., 2006. Messinian Paleoenvironments: New  
3877  
3878 1361 Evidence from the Tyrrhenian Sea (ODP Leg 107). Proc. Ocean Drill. Program, 107 Sci.  
3879  
3880 1362 Results 107, 211–227. doi:10.2973/odp.proc.sr.107.161.1990.  
3881  
3882 1363 Clauzon G., Suc, J.P., Gautier, F., Berger, A., Loutre, M.F., 1996. Alternate interpretation of the  
3883  
3884 1364 Messinian salinity crisis, controversy resolved? *Geology*, 24, 363-366. Doi: 10.1130/0091-  
3885  
3886 1365 7613  
3887  
3888  
3889 1366 Cornet, C., 1968. Le graben médian (zone A) de la Méditerranée occidentale pourrait être  
3890  
3891 1367 pontien. *Sommaire Société Géologique de France* 149.  
3892  
3893 1368 Couto, D. Do, Popescu, S., Suc, J., Melinte-dobrinescu, M.C., Barhoun, N., Gorini, C., Jolivet,  
3894  
3895 1369 L., Poort, J., Jouannic, G., Auxietre, J., 2014. Lago Mare and the Messinian Salinity Crisis :  
3896  
3897 1370 Evidence from the Alboran Sea Lago Mare and the Messinian Salinity Crisis : Evidence  
3898  
3899 1371 from the Alboran Sea (S . Spain). *Mar. Pet. Geol.* 52, 57–76.  
3900  
3901 1372 doi:10.1016/j.marpetgeo.2014.01.018  
3902  
3903 1373 Van Couvering, J.A., Berggren, W.A., Drake, R.E., Aguirre, E., Curtis, G.H., 1976. The terminal  
3904  
3905 1374 Miocene event. *Mar. Micropaleontol.* 1, 263–286.  
3906  
3907  
3908 1375 Debenedetti, A., 1982. The problem of the origin of the salt deposits in the mediterranean and of  
3909  
3910 1376 their relations to the other salt occurrences in the neogene formations of the contiguous  
3911  
3912 1377 regions. *Mar. Geol.* 49, 91–114.  
3913  
3914 1378 Dela Pierre, F., Clari, P., Natalicchio, M., Ferrando, S., Giustetto, R., Lozar, F., Lugli, S., Manzi,

3921  
3922  
3923 1379 V., Roveri, M., Violanti, D., 2014. Flocculent layers and bacterial mats in the mudstone  
3924  
3925 1380 interbeds of the Primary Lower Gypsum unit (Tertiary Piedmont basin, NW Italy): Archives  
3926  
3927  
3928 1381 of palaeoenvironmental changes during the Messinian salinity crisis. *Mar. Geol.* 355, 71–  
3929  
3930 1382 87. doi:10.1016/j.margeo.2014.05.010  
3931  
3932 1383 Derin, B., 2000. Stratigraphic and environments of deposition of Or South 1075–2090 m. Ramat  
3933  
3934 1384 Gan, Derin Consulting & Micropaleontological Services LTD, Internal Isramco Consultant  
3935  
3936 1385 Report 2/00.  
3937  
3938 1386 Ditlevsen, P.D., Andersen, K.K., Svensson, A., 2007. The DO-climate events are probably noise  
3939  
3940 1387 induced: Statistical investigation of the claimed 1470 years cycle. *Clim. Past* 3, 129–134.  
3941  
3942 1388 doi:10.5194/cp-3-129-2007  
3943  
3944 1389 Driussi, O., Maillard, A., Ochoa, D., Lofi, J., Chanier, F., Gaullier, V., Briaais, A., Sage, F.,  
3945  
3946 1390 Sierro, F., Garcia, M., 2015. Messinian Salinity Crisis deposits widespread over the  
3947  
3948 1391 Balearic Promontory: Insights from new high-resolution seismic data. *Mar. Pet. Geol.* 66,  
3949  
3950 1392 41–54. doi:10.1016/j.marpetgeo.2014.09.008  
3951  
3952 1393 Druckman, Y., Buchbinder, B., Martinotti, G.M., Tov, R.S., Aharon, P., 1995. The buried Afik  
3953  
3954 1394 Canyon (eastern Mediterranean, Israel): a case study of a Tertiary submarine canyon  
3955  
3956 1395 exposed in Late Messinian times. *Mar. Geol.* 123, 167–185. doi:10.1016/0025-  
3957  
3958 1396 3227(94)00127-7  
3959  
3960 1397 Ensminger, A., Joly, G., Albrecht, P., 1978. Rearranged steranes in sediments and crude oils.  
3961  
3962 1398 *Tetrahedron Letters.* 1575–1578. doi:https://doi.org/10.1016/S0040-4039(01)94608-8  
3963  
3964 1399 Feng, Y.E., Yankelzon, A., Steinberg, J., Reshef, M., 2016. Lithology and characteristics of the  
3965  
3966 1400 Messinian evaporite sequence of the deep Levant Basin, Eastern Mediterranean. *Mar. Geol.*  
3967  
3968 1401 376, 118–131. doi:10.1016/j.margeo.2016.04.004  
3969  
3970  
3971  
3972  
3973  
3974  
3975  
3976



3977  
3978  
3979 1402 Flecker, R., Ellam, R.M., 2006. Identifying Late Miocene episodes of connection and isolation in  
3980  
3981 1403 the Mediterranean-Paratethyan realm using Sr isotopes. *Sediment. Geol.* 188–189, 189–203.  
3982  
3983 doi:10.1016/j.sedgeo.2006.03.005  
3984 1404  
3985  
3986 1405 Flecker, R., et al., 2015. Evolution of the Late Miocene Mediterranean-Atlantic gateways and  
3987  
3988 1406 their impact on regional and global environmental change. *Earth-Science Reviews*, 150,  
3989  
3990 1407 365–392.  
3991  
3992 1408 Frey-Martinez, J., Hall, B., Cartwright, J., Huuse, M., 2007. Clastic Intrusion at the Base of  
3993  
3994 1409 Deep-water Sands: A Trap-forming Mechanism in the Eastern Mediterranean. *Sand Inject.*  
3995  
3996 1410 *Implic. Hydrocarb. Explor. Prod. AAPG Mem.* 87 49–63. doi:10.1306/1209849M873255  
3997  
3998 1411 Garcia-Castellanos, D., Villaseñor, A., 2011. Messinian salinity crisis regulated by competing  
4000  
4001 1412 tectonics and erosion at the Gibraltar arc. *Nature* 480, 359–363. doi:10.1038/nature10651  
4002  
4003 1413 García-Veigas, J., Cendón, D.I., Gibert, L., Lowenstein, T.K., Artiaga, D., 2018. Geochemical  
4004  
4005 1414 indicators in Western Mediterranean Messinian evaporites: Implications for the salinity  
4006  
4007 1415 crisis. *Mar. Geol.* 403, 197–214. doi:10.1016/j.margeo.2018.06.005  
4008  
4009 1416 Gardosh, M., Druckman, Y., Buchbinder, B., Rybakov, M., 2008. The Levant Basin Offshore  
4010  
4011 1417 Israel: Stratigraphy, Structure, Tectonic Evolution and Implications for Hydrocarbon  
4012  
4013 1418 Exploration - revised edition. Geological Survey of Israel report GSI/4/2008.  
4014  
4015  
4016 1419 Garrison, R.E., Schreiber, B.C., Bernoulli, D., Fabricius, F.H., Kidd, R.B., Mélières, F., 1978.  
4017  
4018 1420 Sedimentary Petrology and Structures of Messinian Evaporitic Sediments in the  
4019  
4020 1421 Mediterranean Sea, Leg 42A, Deep Sea Drilling Project, in: *Initial Reports of the Deep Sea*  
4021  
4022 1422 *Drilling Project 42, No. 1.* pp. 571–612.  
4023  
4024  
4025 1423 Geletti, R., Zgur, F., Del Ben, A., Buriola, F., Fais, S., Fedi, M., Forte, E., Mocnik, A., Paoletti,  
4026  
4027 1424 V., Pipan, M., Ramella, R., Romeo, R., Romi, A., 2014. The Messinian Salinity Crisis: New

4033  
4034  
4035 1425 seismic evidence in the West-Sardinian Margin and Eastern Sardo-Provencal basin (West  
4036  
4037 1426 Mediterranean Sea). *Mar. Geol.* 351, 76–90. doi:10.1016/j.margeo.2014.03.019  
4038  
4039 Gennari, R., Manzi, V., Angeletti, L., Bertini, A., Ceregato, A., Faranda, C., Gliozzi, E.,  
4040 1427  
4041 Menichetti, E., Rosso, A., Roveri, M., Taviani, M., 2013. A shallow water record of the  
4042 1428  
4043 onset of the Messinian salinity crisis in the Adriatic foredeep (Legnagnone section,  
4044 1429  
4045 Northern Apennines). *NU SC. Palaeogeogr. Palaeoclimatol. Palaeoecol.*  
4046 1430  
4047 doi:10.1016/j.palaeo.2013.05.015  
4048 1431  
4049  
4050 1432 Govers, R., 2009. Choking the Mediterranean to dehydration: The Messinian salinity crisis.  
4051  
4052 *Geology* 37, 167–170. doi:10.1130/G25141A.1  
4053 1433  
4054 Gvirtzman, Z., Manzi, V., Calvo, R., Gavrieli, I., Gennari, R., Lugli, S., Reghizzi, M., Roveri,  
4055 1434  
4056 M., 2017. Intra-Messinian truncation surface in the Levant Basin explained by subaqueous  
4057 1435  
4058 dissolution. *Geology* 45, 4–7. doi:10.1130/G39113.1  
4059 1436  
4060  
4061 1437 Gvirtzman, Z., Reshef, M., Buch-leviatan, O., Ben-avraham, Z., 2013a. Intense salt deformation  
4062  
4063 in the Levant Basin in the middle of the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.*  
4064  
4065 1439 379, 108–119. doi:10.1016/j.epsl.2013.07.018  
4066  
4067 1440 Gvirtzman, Z., Reshef, M., Buch-Leviatan, O., Ben-Avraham, Z., 2013b. Intense salt  
4068  
4069 deformation in the Levant Basin in the middle of the Messinian Salinity Crisis. *Earth Planet.*  
4070 1441  
4071 *Sci. Lett.* 379, 108–119. doi:10.1016/j.epsl.2013.07.018  
4072 1442  
4073  
4074 1443 Hall, J.K., Udintsev, G.B., Odnikov, Y.Y., 1994. The bottom relief of the Levantine Sea, in  
4075  
4076 1444 *Geologic Structure of the Northeastern Mediterranean*. Krashennnikov, V. A., Hall, J.K.,  
4077  
4078 1445 pp. 5–32, Historical Productions-Hall Ltd., Jerusalem.  
4079  
4080 1446 Hall, J.K., Lippman, S., Gardosh, M., Tibor, G., Sade, A.R., Sade, H., 2015. A New Bathymetric  
4081  
4082 1447 Map for the Israeli EEZ: Preliminary Results. State of Israel, Ministry of National  
4083  
4084  
4085  
4086  
4087  
4088

4089  
4090  
4091 1448 Infrastructure Energy and Water, Jerusalem.  
4092  
4093 1449 Hardie, L.A., Lowenstein, T.K., 2004. Did the Mediterranean Sea Dry Out During the Miocene?  
4094  
4095 a Reassessment of the Evaporite Evidence From Dsdp Legs 13 and 42a Cores. *J. Sediment.*  
4096 1450  
4097  
4098 1451 *Res.* 74, 453–461. doi:10.1306/112003740453  
4099  
4100 1452 Hawie, N., Deschamps, R., Nader, F.H., Gorini, C., 2013a. Sedimentological and stratigraphic  
4101  
4102 1453 evolution of northern Lebanon since the Late Cretaceous: implications for the Levant  
4103  
4104 1454 margin and basin. doi:10.1007/s12517-013-0914-5  
4105  
4106 1455 Hawie, N., Gorini, C., Deschamps, R., Nader, F.H., Montadert, L., Granjeon, D., Baudin, F.,  
4107  
4108 1456 2013b. Tectono-stratigraphic evolution of the northern Levant Basin (offshore Lebanon).  
4109  
4110 1457 *Mar. Pet. Geol.* 48, 392–410. doi:10.1016/j.marpetgeo.2013.08.004  
4111  
4112  
4113 1458 Hernández-Molina F.J, et al., 2014. Onset of Mediterranean outflow into the North Atlantic.  
4114  
4115 1459 *Science* 344, 1244–1250. doi: 10.1126/science.1251306  
4116  
4117 1460 Hilgen, F., Kuiper, K., Krijgsman, W., Snel, E., Laan, E. Van Der, van der Laan, E., 2007.  
4118  
4119 1461 Astronomical tuning as the basis for high resolution chronostratigraphy: The intricate  
4120  
4121 1462 history of the Messinian Salinity Crisis. *Stratigraphy* 4, 231–238.  
4122  
4123 1463 Hilgen, F.J., Bissoli, L., Iaccarino, S., Krijgsman, W., Meijer, R., Negri, A., Villa, G., 2000.  
4124  
4125 1464 Integrated stratigraphy and astrochronology of the Messinian GSSP at Oued Akrech  
4126  
4127 1465 (Atlantic Morocco). *Earth Planet. Sci. Lett.* 182, 237–251. doi:10.1016/S0012-  
4128  
4129 1466 821X(00)00247-8  
4130  
4131  
4132 1467 Hilgen, F.J., Krijgsman, W., 1999. Cyclostratigraphy and astrochronology of the Tripoli  
4133  
4134 1468 diatomite formation (pre-evaporite Messinian, Sicily, Italy). *Terra Nov.* 11, 16–22.  
4135  
4136 1469 doi:10.1046/j.1365-3121.1999.00221.x  
4137  
4138 1470 Hilgen, F.J., Krijgsman, W., Langereis, C.G., Lourens, L.J., Santarelli, A., Zachariasse, W.J.,  
4139  
4140  
4141  
4142  
4143  
4144

4145  
4146  
4147 1471 1995. Extending the astronomical (polarity) time scale into the Miocene. *Earth Planet. Sci.*  
4148  
4149  
4150 1472 *Lett.* 136, 495–510. doi:10.1016/0012-821X(95)00207-S  
4151  
4152 1473 Hsü, K.J., 1973. The desiccated deep-basin model for the Messinian events, in: Drooger, C.W.  
4153  
4154 1474 (Ed.), *Messinian Events in the Mediterranean*. North-Holland Publ. Co., Amsterdam, pp.  
4155  
4156 1475 60–67.  
4157  
4158 1476 Hsü, K. J., Ryan, W.B.F., Schreiber, B.C., 1973. Petrography of a halite sample from hole 134 -  
4159  
4160 1477 balearic abyssal plain, in: *Initial Reports of the Deep Sea Drilling Project 13, No. Part 2*. pp.  
4161  
4162 1478 708–711.  
4163  
4164  
4165 1479 Hsü, K.J., Montadert, L., Bernoulli, D., Bizon, G., Cita, M., Erickson, A., Fabricius, F., Garrison,  
4166  
4167 1480 R.E., Kidd, R.B., Mélières, F., Müller, C., Wright, R.C., 1978a. Site 374: Messina Abyssal  
4168  
4169 1481 Plain, in: *Initial Reports of the Deep Sea Drilling Project: DSDP Volume XLII Part 1*. p. 43.  
4170  
4171 1482 doi:10.2973/dsdp.proc.42-1.105.1978  
4172  
4173  
4174 1483 Hsü, K.J., Montadert, L., Bernoulli, D., Bizon, G., Cita, M., Erickson, A., Fabricius, F., Garrison,  
4175  
4176 1484 R.E., Kidd, R.B., Mélières, F., Müller, C., Wright, R.C., 1978b. Sites 375 and 376: Florence  
4177  
4178 1485 Rise, in: *Initial Reports of the Deep Sea Drilling Project: DSDP Volume XLII Part 1*. p. 86.  
4179  
4180 1486 Hüsing, S.K., Cascella, A., Hilgen, F.J., Krijgsman, W., Kuiper, K.F., Turco, E., Wilson, D.,  
4181  
4182 1487 2010. Astrochronology of the Mediterranean Langhian between 15 . 29 and 14 . 17 Ma.  
4183  
4184 1488 *Earth Planet. Sci. Lett.* 290, 254–269. doi:10.1016/j.epsl.2009.12.002  
4185  
4186 1489 Hüsing, S.K., Kuiper, K.F., Link, W., Hilgen, F.J., Krijgsman, W., 2009. The upper Tortonian-  
4188  
4189 1490 lower Messinian at Monte dei Corvi (Northern Apennines, Italy): Completing a  
4190  
4191 1491 Mediterranean reference section for the Tortonian Stage. *Earth Planet. Sci. Lett.* 282, 140–  
4192  
4193 1492 157. doi:10.1016/j.epsl.2009.03.010  
4194  
4195 1493 Karakitsios, V., Cornée, J.J., Tsourou, T., Moissette, P., Kontakiotis, G., Agiadi, K.,  
4196  
4197  
4198  
4199  
4200

4201  
4202  
4203 1494 Manoutsoglou, E., Triantaphyllou, M., Koskeridou, E., Drinia, H., Roussos, D., 2017.  
4204  
4205 1495 Messinian salinity crisis record under strong freshwater input in marginal, intermediate, and  
4206  
4207 deep environments: The case of the North Aegean. *Palaeogeogr. Palaeoclimatol.*  
4208 1496  
4209  
4210 1497 *Palaeoecol.* 485, 316–335. doi:10.1016/j.palaeo.2017.06.023  
4211  
4212 1498 Keogh, S.M., Butler, R.W.H., 1999. The Mediterranean water body in the late Messinian:  
4213  
4214 1499 interpreting the record from marginal basins on Sicily. *J. Geol. Soc. London.* 156, 837–846.  
4215  
4216 doi:10.1144/gsjgs.156.4.0837  
4217 1500  
4218  
4219 1501 Krijgsman, W., Blanc-Valleron, M.M., Flecker, R., Hilgen, F.J., Kouwenhoven, T.J., Merle, D.,  
4220  
4221 1502 Orszag-Sperber, F., Rouchy, J.M., 2002. The onset of the Messinian salinity crisis in the  
4222  
4223 1503 Eastern Mediterranean (Pissouri Basin, Cyprus). *Earth Planet. Sci. Lett.* 194, 299–310.  
4224  
4225 doi:10.1016/S0012-821X(01)00574-X  
4226 1504  
4227  
4228 1505 Krijgsman, W., Fortuin, A.R., Hilgen, F.J., Sierro, F.J., 2001. Astrochronology for the Messinian  
4229  
4230 1506 Sorbas basin (SE Spain) and orbital (precessional) forcing for evaporite cyclicity. *Sediment.*  
4231  
4232 1507 *Geol.* 140, 43–60. doi:10.1016/S0037-0738(00)00171-8  
4233  
4234 1508 Krijgsman, W., Garces, M., Agusti, J., Raffi, I., Taberner, C., Zachariasse, W.J., 2000. The  
4235  
4236 1509 “Tortonian salinity crisis” of the eastern Betics (Spain). *Earth Planet. Sci. Lett.* 181, 497–  
4237  
4238 1510 511. doi:10.1016/S0012-821X(00)00224-7  
4239  
4240 1511 Krijgsman, W., Hilgen, F.J., Negri, A., Wijbrans, J.R., Zachariasse, W.J., 1997. The Monte del  
4241  
4242 1512 Casino section (Northern Apennines, Italy): A potential Tortonian/Messinian boundary  
4243  
4244 1513 stratotype? *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 133, 27–47. doi:10.1016/S0031-  
4245  
4246 1514 0182(97)00039-4  
4247  
4248  
4249 1515 Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999. Chronology, causes and  
4250  
4251 1516 progression of the Messinian salinity crisis. *Nature* 400, 652–655. doi:10.1038/23231.  
4252  
4253  
4254  
4255  
4256

4257  
4258  
4259 1517 Krijgsman, W., Meijer, P.T., 2008. Depositional environments of the Mediterranean “Lower  
4260  
4261 1518 Evaporites” of the Messinian salinity crisis: Constraints from quantitative analyses. *Mar.*  
4262  
4263  
4264 1519 *Geol.* doi:10.1016/j.margeo.2008.04.010  
4265  
4266 1520 Krijgsman, W., Stoica, M., Vasiliev, I., Popov, V. V., 2010. Rise and fall of the Paratethys Sea  
4267  
4268 1521 during the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.* 290, 183–191.  
4269  
4270 1522 doi:10.1016/j.epsl.2009.12.020.  
4271  
4272  
4273 1523 Lange, G.J. De, Krijgsman, W., 2010. Messinian salinity crisis: A novel unifying shallow  
4274  
4275 1524 gypsum / deep dolomite formation mechanism. *Mar. Geol.* 275, 273–277.  
4276  
4277 1525 doi:10.1016/j.margeo.2010.05.003  
4278  
4279 1526 Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-  
4280  
4281 1527 term numerical solution for the insolation quantities of the Earth. *Astron. As-trophys.*  
4282  
4283 1528 *Astron. Astrophys.* 428, 261–285. doi:10.1051/0004-6361:20041335  
4284  
4285 1529 Leila, M., Kora, M.A., Ahmed, M.A., Ghanem, A., 2016. Sedimentology and reservoir  
4286  
4287 1530 characterization of the Upper Miocene Qawasim Formation, El-Tamad Oil Field onshore  
4288  
4289 1531 Nile Delta, Egypt. *Arab. J. Geosci.* 9, 1–13. doi:10.1007/s12517-015-2088-9  
4290  
4291  
4292 1532 Lofi, J., Camerlenghi, A., 2014. Messinian Salinity Crisis - DREAM (Deep-sea Record of  
4293  
4294 1533 Mediterranean Messinian events) drilling projects Messinian Salinity Crisis - DREAM  
4295  
4296 1534 (Deep-sea Record of Mediterranean Messinian events) drilling projects, in: EGU. Vienna, p.  
4297  
4298 1535 1.  
4299  
4300 1536 Lofi, J., Sage, F., Deverchere, J., Loncke, L., Maillard, A., Gaullier, V., Thion, I., Gillet, H.,  
4301  
4302 1537 Guennoc, P., Gorini, C., 2011. Refining our knowledge of the Messinian salinity crisis  
4303  
4304 1538 records in the offshore domain through multi-site seismic analysis. *Bull. la Soc. Geol. Fr.*  
4305  
4306 1539 182, 163–180. doi:10.2113/gssgfbull.182.2.163  
4307  
4308  
4309  
4310  
4311  
4312

4313  
4314  
4315 1540 Lohmann, J., Ditlevsen, P.D., 2018. Random and externally controlled occurrences of  
4316  
4317 1541 Dansgaard-Oeschger events. *Clim. Past* 14, 609–617. doi:10.5194/cp-14-609-2018  
4318  
4319 1542 Lugli, S., Gennari, R., Gvirtzman, Z., Manzi, V., Roveri, M., Schreiber, B.C., 2013. Evidence of  
4320  
4321 clastic evaporites in the canyons of the Levant Basin (Israel): implications for the Messinian  
4322 1543 Salinity Crisis. *J. Sediment. Res.* 83, 942–954. doi:10.2110/jsr.2013.72  
4323  
4324 1544  
4325  
4326 1545 Lugli, S., Manzi, V., Roveri, M., Schreiber, B.C., 2015. The deep record of the Messinian  
4327  
4328 1546 salinity crisis: Evidence of a non-desiccated Mediterranean Sea. *Palaeogeogr.*  
4329  
4330 1547 *Palaeoclimatol. Palaeoecol.* 433, 201–218. doi:10.1016/j.palaeo.2015.05.017  
4331  
4332 1548 Lugli, S., Schreiber, B.C., Triberti, B., 1999. Giant polygons in the Realmonte Mine (Agrigento,  
4333  
4334 1549 Sicily); evidence for the desiccation of a Messinian halite basin. *J. Sediment. Res.* 69, 764–  
4335  
4336 1550 771. doi:10.2110/jsr.69.764  
4337  
4338  
4339 1551 McArthur, J. M., Howarth, R. J., Shield, G. A., 2012. Chapter 7: Strontium Isotope Stratigraphy.  
4340  
4341 1552 In *The Geologic Time Scale*, eds. F. M. Gredstein, J. G. Ogg, M. D. Schmotz & G. M. Ogg,  
4342  
4343 1553 1144 Elsevier.  
4344  
4345 1554 Madof, A.S., Bertoni, C., Lofi, J., 2019. Discovery of vast fluvial deposits provides evidence for  
4346  
4347 1555 drawdown during the late Miocene Messinian salinity crisis. *Geology* 47, 171–174.  
4348  
4349 1556 doi:10.1130/G45873.1  
4350  
4351 1557 Manzi, V., Gennari, R., Hilgen, F., Krijgsman, W., Lugli, S., 2013. Age refinement of the  
4352  
4353 1558 Messinian salinity crisis onset in the Mediterranean. doi:10.1111/ter.12038  
4354  
4355  
4356 1559 Manzi, V., Gennari, R., Lugli, S., Persico, D., Reghizzi, M., Roveri, M., Schreiber, B.C., Calvo,  
4357  
4358 1560 R., Gavrieli, I., Gvirtzman, Z., 2018. The onset of the Messinian salinity crisis in the deep  
4359  
4360 1561 Eastern Mediterranean basin. *Terra Nov.* 38, 42–49. doi:10.1111/ter.12325  
4361  
4362 1562 Manzi, V., Gennari, R., Lugli, S., Roveri, M., Scafetta, N., Charlotte, B., 2012. High-frequency  
4363  
4364  
4365  
4366  
4367  
4368

4369  
4370  
4371 1563 cyclicity in the Mediterranean Messinian evaporites: evidence for solar-lunar climate  
4372 forcing. *J. Sediment. Res.* 82, 991–1005. doi:10.2110/jsr.2012.81  
4373  
4374 1564  
4375  
4376 1565 Manzi, V., Lugli, S., Roveri, M., Dela Pierre, F., Gennari, R., Lozar, F., Natalicchio, M.,  
4377  
4378 1566 Schreiber, B.C., Taviani, M., Turco, E., 2015. The Messinian salinity crisis in Cyprus: A  
4379  
4380 1567 further step towards a new stratigraphic framework for Eastern Mediterranean. *Basin Res.*  
4381  
4382 1568 28, 207–236. doi:10.1111/bre.12107  
4383  
4384 1569 Manzi, V., Lugli, S., Roveri, M., Schreiber, B.C., 2009. A new facies model for the Upper  
4385  
4386 1570 Gypsum of Sicily (Italy): Chronological and palaeoenvironmental constraints for the  
4387  
4388 1571 Messinian salinity crisis in the Mediterranean. *Sedimentology* 56, 1937–1960.  
4389  
4390 1572 doi:10.1111/j.1365-3091.2009.01063.x  
4391  
4392  
4393 1573 Manzi, V., Lugli, S., Roveri, M., Schreiber, B.C., Gennari, R., 2011. The Messinian “Calcare di  
4394  
4395 1574 Base” (Sicily, Italy) revisited. *Bull. Geol. Soc. Am.* 123, 347–370. doi:10.1130/B30262.1  
4396  
4397 1575 Marzocchi, A., Lunt, D.J., Flecker, R., Bradshaw, C.D., Farnsworth, A., Hilgen, F.J., 2015.  
4398  
4399 1576 Orbital control on late Miocene climate and the North African monsoon: Insight from an  
4400  
4401 1577 ensemble of sub-precessional simulations. *Clim. Past* 11, 1271–1295. doi:10.5194/cp-11-  
4402  
4403 1578 1271-2015  
4404  
4405 1579 Meilijson, A., Ashckenazi-Polivoda, S., Ron-Yankovich, L., Illner, P., Alsenz, H., Speijer, R.P.,  
4406  
4407 1580 Almogi-Labin, A., Feinstein, S., Berner, Z., Püttmann, W., Abramovich, S., 2014.  
4408  
4409  
4410 1581 Chronostratigraphy of the Upper Cretaceous high productivity sequence of the southern  
4411  
4412 1582 Tethys, Israel. *Cretac. Res.* 50. doi:10.1016/j.cretres.2014.04.006  
4413  
4414 1583 Meilijson, A., Steinberg, J., Hilgen, F., Bialik, O.M., Waldmann, N.D., Makovsky, Y., 2018.  
4415  
4416 1584 Deep-basin evidence resolves a 50-year-old debate and demonstrates synchronous onset of  
4417  
4418 1585 Messinian evaporite deposition in a non-desiccated Mediterranean. *Geology* 46, 4–7.  
4419  
4420  
4421  
4422  
4423  
4424



4425  
4426  
4427 1586 Müller, D.W., Mueller, P.A., 1991. Origin and age of the Mediterranean Messinian evaporites:  
4428  
4429 1587 implications from Sr isotopes. *Earth Planet. Sci. Lett.* doi:10.1016/0012-821X(91)90039-K  
4430  
4431  
4432 1588 Nam, M., Görür, N., Flecker, R., Sak, M., Tüno, C., Ellam, R., Krijgsman, W., Vincent, S.,  
4433  
4434 1589 Dikba, A., 2006. Paratethyan–Mediterranean connectivity in the Sea of Marmara region  
4435  
4436 1590 (NW Turkey) during the Messinian. *Sediment. geo* 188–189, 171–187.  
4437  
4438 1591 doi:10.1016/j.sedgeo.2006.03.004  
4439  
4440 1592 Netzeband, G.L., Hübscher, C.P., Gajewski, D., 2006. The structural evolution of the Messinian  
4441  
4442 1593 evaporites in the Levantine Basin. *Mar. Geol.* 230, 249–273.  
4443  
4444 1594 doi:10.1016/j.margeo.2006.05.004  
4445  
4446 1595 Ochoa, D., Sierro, F.J., Lofi, J., Maillard, A., Flores, J.A., Suarez, M., 2015. Synchronous onset  
4447  
4448 1596 of the Messinian evaporite precipitation: First Mediterranean offshore evidence. *Earth*  
4449  
4450 1597 *Planet. Sci. Lett.* 427, 112–124. doi:10.1016/j.epsl.2015.06.059  
4451  
4452 1598 Ogniben, L., 1957. Petrografia della Serie Solfifera Siciliana e considerazioni geologiche  
4453  
4454 1599 relative. *Memorie Descrittive della Carta Geologica d'Italia* 33, 1–275.  
4455  
4456 1600 Ohneiser, C., Florindo, F., Stocchi, P., Roberts, A.P., DeConto, R.M., Pollard, D., 2015.  
4457  
4458 1601 Antarctic glacio-eustatic contributions to late Miocene Mediterranean desiccation and  
4459  
4460 1602 reflooding. *Nat. Commun.* 6, 8765. doi:10.1038/ncomms9765  
4461  
4462 1603 Peters, K.E., A.E. Kontorovich, J.M.M., 1993. Geochemistry of selected oils and rocks from the  
4463  
4464 1604 central portion of the west Siberian Basin, Russia. *Am. Assoc. Pet. Geol. Bull.* 77, 87–863.  
4465  
4466 1605 Peters, K.E., 1986. Guidelines for Evaluating Petroleum Source Rock Using Programmed  
4467  
4468 1606 Pyrolysis. *Am. Assoc. Pet. Geol. Bull.* 70, 318–329. doi:10.1306/94885688-1704-11D7-  
4469  
4470 1607 8645000102C1865D  
4471  
4472 1608 Peters, K.E., Rohrback, B.G., Kaplan, I.R., 1980. Laboratory-simulated thermal maturation of  
4473  
4474  
4475  
4476  
4477  
4478  
4479  
4480

4481  
4482  
4483 1609 Recent sediments. *Phys. Chem. Earth* 12, 547–557. doi:10.1016/0079-1946(79)90136-8  
4484  
4485 1610 Peters, K.E., Walters Clifford C, Moldowan, J.M., 2005. *The Biomarker Guide, Biomarkers and*  
4486  
4487 *Isotopes in Petroleum Exploration and Earth History, Volume 2.* Cambridge.  
4488  
4489 doi:10.1017/s0016756806212056  
4490 1612  
4491  
4492 1613 Rashid, H., Grosjean, E., 2006. Detecting the source of Heinrich layers: An organic geochemical  
4493  
4494 1614 study. *Paleoceanography* 21. doi:10.1029/2005PA001240  
4495  
4496 1615 Reiche, S., Hübscher, C., Beitz, M., 2014. Fault-controlled evaporite deformation in the Levant  
4497  
4498 1616 Basin, Eastern Mediterranean. *Mar. Geol.* 354, 53–68. doi:10.1016/j.margeo.2014.05.002  
4499  
4500 1617 Richter-Bernburg, G., 1996. Zechstein-Anhydrite: Fazies und Genese, *Geologisches Jahrbuch.*  
4501  
4502 1618 Reihe A, Allgemeine und regionale Geologie Bundesrepublik Deutschland und  
4503  
4504 1619 Nachbargebiete, Tektonik, Stratigraphie, Paläontologie. Bundesanstalt für  
4505  
4506 1620 Geowissenschaften und Rohstoffe.  
4507  
4508  
4509 1621 Roberts, G., Peace, D., 2007. Hydrocarbon plays and prospectivity of the Levantine basin,  
4510  
4511 1622 offshore Lebanon and Syria from modern seismic data. *GeoArabia* 12, 99–124.  
4512  
4513 1623 Rouchy, J.M., Caruso, A., 2006. The Messinian salinity crisis in the Mediterranean basin : A  
4514  
4515 1624 reassessment of the data and an integrated scenario. *Sediment. Geol.* 188–189, 35–67.  
4516  
4517 1625 doi:10.1016/j.sedgeo.2006.02.005  
4518  
4519 1626 Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V., Sierro, F.J., Bertini, A.,  
4520  
4521 1627 Camerlenghi, A., De Lange, G., Govers, R., Hilgen, F.J., Hübscher, C., Meijer, P.T., Stoica,  
4522  
4523 1628 M., 2014a. The Messinian Salinity Crisis: Past and future of a great challenge for marine  
4524  
4525 1629 sciences. *Mar. Geol.* 352, 25–58. doi:10.1016/j.margeo.2014.02.002  
4526  
4527  
4528 1630 Roveri, M., Gennari, R., Ligi, M., Lugli, S., Manzi, V., Reghizzi, M., 2019. The synthetic  
4529  
4530 1631 seismic expression of the Messinian salinity crisis from onshore records: implications for  
4531  
4532  
4533  
4534  
4535  
4536

4537  
4538  
4539 1632 shallow- to deep-water correlations. *Basin Res.* doi:10.1111/bre.12361  
4540  
4541  
4542 1633 Roveri, M., Lugli, S., Manzi, V., Gennari, R., Schreiber, B.C., 2014b. High-resolution strontium  
4543  
4544 1634 isotope stratigraphy of the messinian deep Mediterranean basins: Implications for marginal  
4545  
4546 1635 to central basins correlation. *Mar. Geol.* 349, 113–125. doi:10.1016/j.margeo.2014.01.002  
4547  
4548 1636 Roveri, M., Manzi, V., Bergamasco, A., Falcieri, F.M., Gennari, R., Lugli, S., Schreiber, B.C.,  
4549  
4550 1637 2014c. Dense shelf water cascading and messinian canyons: A new scenario for the  
4551  
4552 1638 mediterranean salinity crisis. *Am. J. Sci.* 314, 751–784. doi:10.2475/05.2014.03  
4553  
4554  
4555 1639 Rullkötter, J., R.M., 1988. Natural and artificial maturation of biological markers in a Toarcian  
4556  
4557 1640 shale from northern Germany, in: Novelli, L.M. and L. (Ed.), *Advances in Organic*  
4558  
4559 1641 *Geochemistry* 1987. Oxford Pergamon Press, pp. 639–645.  
4560  
4561 1642 Ryan, W.B.F., 2011. Geodynamic responses to a two-step model of the Messinian salinity crisis.  
4562  
4563 1643 *Bull. la Soc. Geol. Fr.* 182, 73–78. doi:10.2113/gssgfbull.182.2.73  
4564  
4565 1644 Ryan, W.B.F., 2008. Modeling the magnitude and timing of evaporative drawdown during the  
4566  
4567 1645 Messinian salinity crisis. *Stratigraphy* 5, 227–243.  
4568  
4569  
4570 1646 Ryan, W.B.F., 1978. Messinian badlands on the southeastern margin of the Mediterranean Sea.  
4571  
4572 1647 *Mar. Geol.* 27, 349–363. doi:10.1016/0025-3227(78)90039-7  
4573  
4574 1648 Ryan, W.B.F., 1976. Quantitative evaluation of the depth of the western Mediterranean before,  
4575  
4576 1649 during and after the late Miocene salinity crisis. *Sedimentology* 23, 791–813.  
4577  
4578  
4579 1650 Ryan, W.B.F., 1973. Geodynamic implications of the Messinian crisis of salinity, in: Drooger,  
4580  
4581 1651 D.W. (Ed.), *Messinian Events in the Mediterranean*. Elsevier, Amsterdam, pp. 26–38.  
4582  
4583 1652 Ryan, W.B.F., Cita, M.B., 1978. The nature and distribution of Messinian erosional surfaces -  
4584  
4585 1653 Indicators of a several-kilometer-deep Mediterranean in the Miocene. *Mar. Geol.*  
4586  
4587 1654 doi:10.1016/0025-3227(78)90032-4  
4588  
4589  
4590  
4591  
4592

4593  
4594  
4595 1655 Ryan, W.B.F., Hsü, K.J., Cita, M.B., Dumitrica, P., Lort, J., Maync, W., Nesteroff, W.D., Pautot,  
4596  
4597 G., Stradner, H., 2007. DSDP Volume XIII: 6. Balearic Rise - Site 124. The Shipboard  
4598 1656  
4599 Scientific Party. doi:10.2973/dsdp.proc.13.1973  
4600 1657  
4601  
4602 1658 Ryan, W.B.F., Stanley, D.J., Hersey, J.B., Fahlquist, D.A., Allan, T.D., 1971. The tectonics and  
4603  
4604 geology of the Mediterranean Sea. In: Maxwell, A.E. (Ed.), *The Sea*. Wiley- Interscience,  
4605 1659  
4606 New York, pp. 387–492.  
4607 1660  
4608  
4609 1661 Scafetta, N., Milani, F., Bianchini, A., Ortolani, S., 2016. On the astronomical origin of the  
4610  
4611 Hallstatt oscillation found in radiocarbon and climate records throughout the Holocene.  
4612  
4613 Earth-Science Rev. 162, 24–43. doi:10.1016/j.earscirev.2016.09.004  
4614 1663  
4615 1664 Scalán, E.S., Smith, J.E., 1970. An improved measure of the odd-even predominance in the  
4616  
4617 normal alkanes of sediment extracts and petroleum. *Geochim. Cosmochim. Acta* 34, 611–  
4618  
4619 620. doi:10.1016/0016-7037(70)90019-0  
4620 1666  
4621 1667 Schmalz, R.F., 1969. Deep-Water Evaporite Deposition: A Genetic Model. *Am. Assoc. Pet.*  
4622  
4623 *Geol. Bull.* 53, 798–823. doi:10.1306/5D25C7FD-16C1-11D7-8645000102C1865D  
4624 1668  
4625  
4626 1669 Schulz, M., 2002. On the 1470-year pacing of Dansgaard-Oeschger warm events.  
4627  
4628 *Paleoceanography* 17, 4-1-4–9. doi:10.1029/2000PA000571  
4629 1670  
4630 1671 Schulz, M., Mudelsee, M., 2002. REDFIT: Estimating red-noise spectra directly from unevenly  
4631  
4632 spaced paleoclimatic time series. *Comput. Geosci.* 28, 421–426. doi:10.1016/S0098-  
4633  
4634 3004(01)00044-9  
4635 1673  
4636 1674 Selli, R., 1954. Il Bacino del Metauro. *Giornale di Geologia* 24, 1–294.  
4637  
4638  
4639 1675 Sepúlveda, J., Wendler, J.E., Summons, R.E., Hinrichs, K.U., 2009. Rapid Resurgence of Marine  
4640  
4641 Productivity After the Cretaceous-Paleogene Mass Extinction. *Science* (80-. ). 326, 129–  
4642  
4643 132.  
4644 1677  
4645  
4646  
4647  
4648

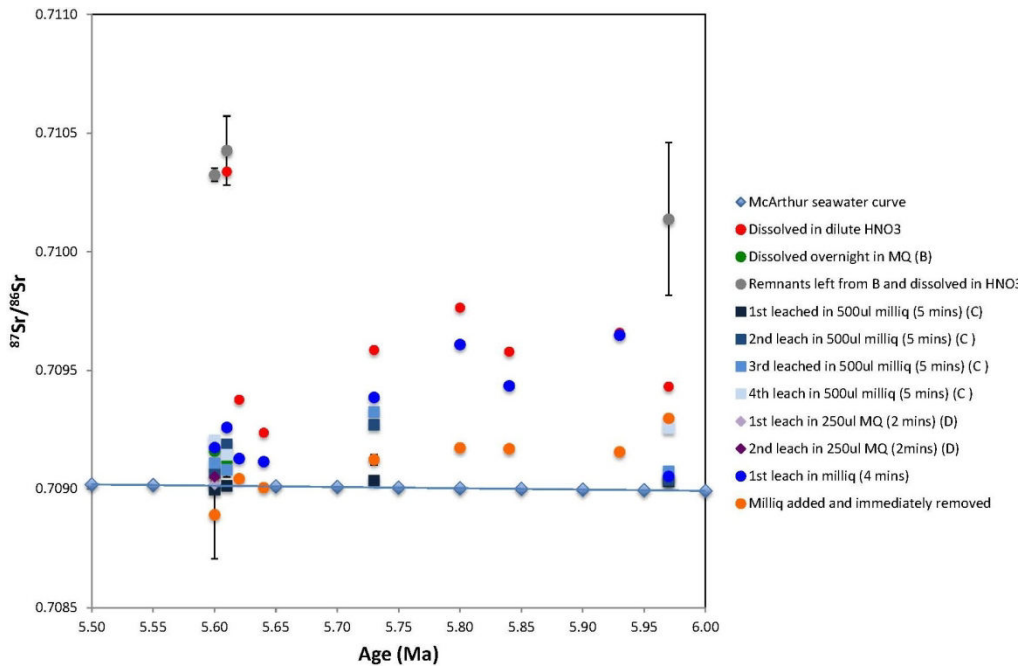
4649  
4650  
4651 1678 Sierro, F.J., Hilgen, F.J., Krijgsman, W., Flores, J.A., 2001. The Abad composite (SE Spain): A  
4652  
4653 1679 Messinian reference section for the Mediterranean and the APTS. *Palaeogeogr.*  
4654  
4655  
4656 1680 *Palaeoclimatol. Palaeoecol.* 168, 141–169. doi:10.1016/S0031-0182(00)00253-4  
4657  
4658 1681 Simon, D., Marzocchi, A., Flecker, R., Lunt, D.J., Hilgen, F.J., Meijer, P.T., 2017. Quantifying  
4659  
4660 1682 the Mediterranean freshwater budget throughout the late Miocene: New implications for  
4661  
4662 1683 sapropel formation and the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.* 472, 25–37.  
4663  
4664 1684 doi:10.1016/j.epsl.2017.05.013  
4665  
4666 1685 Simon, D., Meijer, P.T., 2017. Salinity stratification of the Mediterranean Sea during the  
4667  
4668 1686 Messinian crisis: A first model analysis. *Earth Planet. Sci. Lett.* 479, 366–376.  
4669  
4670 1687 doi:10.1016/j.epsl.2017.09.045  
4671  
4672  
4673 1688 Sirota, I., Ali, A., Lensky, N.G., 2016. Seasonal variations of halite saturation in the Dead Sea.  
4674  
4675 1689 *Water Resour. Res.* 52. doi:10.1002/2014WR016618  
4676  
4677 1690 Sirota, I., Enzel, Y., Lensky, N.G., 2017. Temperature seasonality control on modern halite  
4678  
4679 1691 layers in the Dead Sea: In situ observations. *Bull. Geol. Soc. Am.* 129, 1181–1194.  
4680  
4681 1692 doi:10.1130/B31661.1  
4682  
4683 1693 Sonnenfeld, P., Finetti, I., 2011. Messinian Evaporites in the Mediterranean: A Model of  
4684  
4685 1694 Continuous Inflow and Outflow, in: *Geological Evolution of the Mediterranean Basin.*  
4686  
4687 1695 doi:10.1007/978-1-4613-8572-1-17  
4688  
4689  
4690 1696 Sonnenfeld, P., Hudec, P.P., 1983. Clay laminations in Halite: Their Cause and Effect, in: *Sixth*  
4691  
4692 1697 *International Symposium on Salt.* pp. 51–56.  
4693  
4694 1698 Steinberg, J., Gvirtzman, Z., Folkman, Y., 2010. New age constraints on the evolution of the Mt  
4695  
4696 1699 Carmel structure and its implications on a Late Miocene extensional phase of the Levant  
4697  
4698 1700 continental margin. *J. Geol. Soc. London.* 167, 203–216. doi:10.1144/0016-76492009-089  
4699  
4700  
4701  
4702  
4703  
4704

4705  
4706  
4707 1701 Steinberg, J., Gvirtzman, Z., Folkman, Y., Garfunkel, Z., 2011. Origin and nature of the rapid  
4708  
4709 late Tertiary filling of the Levant Basin. *Geology* 39, 355–358. doi:10.1130/G31615.1  
4710 1702  
4711  
4712 1703 Steinhilber, F., Abreu, J.A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkila, U., Kubik,  
4713  
4714 1704 P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H., Wilhelms, F.,  
4715  
4716 1705 2012. 9,400 Years of Cosmic Radiation and Solar Activity From Ice Cores and Tree Rings.  
4717  
4718 1706 *Proc. Natl. Acad. Sci.* 109, 5967–5971. doi:10.1073/pnas.1118965109  
4719  
4720 1707 Steinhorn, I., 1983. In situ salt precipitation at the Dead Sea. *Limnol. Oceanogr.* 28, 580–583.  
4721  
4722 1708 doi:10.4319/lo.1983.28.3.0580  
4723  
4724 1709 Stiller, M., Gat, J.R., Kaushansky, P., 1997. Halite Precipitation and Sediment Deposition As  
4725  
4726 Measured in Sediment Traps Deployed in the Dead Sea: 1981-1983. *Dead Sea lake its*  
4727 1710  
4728 settings 161–170.  
4729 1711  
4730  
4731 1712 Stoica, M., Krijgsman, W., Fortuin, A., Gliozzi, E., 2016. Paratethyan ostracods in the Spanish  
4732  
4733 1713 Lago-Mare: More evidence for interbasinal exchange at high Mediterranean sea level.  
4734  
4735 1714 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 441, 854–870. doi:10.1016/j.palaeo.2015.10.034  
4736  
4737 1715 ten Haven, H.L., de Leeuw, J.W., Schenck, P.A., 1985. Organic geochemical studies of a  
4738  
4739 1716 Messinian evaporitic basin, northern Apennines (Italy) I: Hydrocarbon biological markers  
4740  
4741 1717 for a hypersaline environment. *Geochim. Cosmochim. Acta* 49, 2181–2191.  
4742  
4743 1718 Tomas, C.R., 1996. *Identifying Marine Phytoplankton*, Academic Press Inc. San Diego.  
4744  
4745 1719 doi:10.1016/S0025-3227(97)81154-1  
4746  
4747  
4748 1720 Topper, R. P. M., Flecker, R., Meijer, P., Wortel, M. J. R., 2011. A box model of the Late  
4749  
4750 1721 Miocene Mediterranean Sea: implications from combined  $87\text{Sr}/86\text{Sr}$  and salinity data.  
4751  
4752 1722 *Paleoceanography*, 26.  
4753  
4754 1723 Topper, R.P.M., Lugli, S., Manzi, V., Roveri, M., Meijer, P.T., 2014. Precessional control of Sr  
4755  
4756  
4757  
4758  
4759  
4760

4761  
4762  
4763 1724 ratios in marginal basins during the Messinian Salinity Crisis? *Geochemistry, Geophys.*  
4764  
4765 *Geosystems* 15, 1926–1944. doi:10.1002/2013GC005192  
4766 1725  
4767  
4768 1726 van den Berg, B.C.J., Sierro, F.J., Hilgen, F.J., Flecker, R., Larrasoña, J.C., Krijgsman, W.,  
4769  
4770 1727 Flores, J.A., Mata, M.P., Bellido Martín, E., Civiş, J., González-Delgado, J.A., 2015.  
4771  
4772 1728 Astronomical tuning for the upper Messinian Spanish Atlantic margin: Disentangling basin  
4773  
4774 1729 evolution, climate cyclicity and MOW. *Glob. Planet. Change* 135, 89–103.  
4775  
4776 1730 doi:10.1016/j.gloplacha.2015.10.009  
4777  
4778 1731 Vasiliev, I., Mezger, E.M., Lugli, S., Reichert, G., Manzi, V., Roveri, M., 2017. How dry was the  
4779  
4780 1732 Mediterranean during the Messinian salinity crisis? *Palaeogeogr. Palaeoclimatol.*  
4781  
4782 *Palaeoecol.* 471, 120–133. doi:10.1016/j.palaeo.2017.01.032  
4783 1733  
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1735 **Supplementary Figures**



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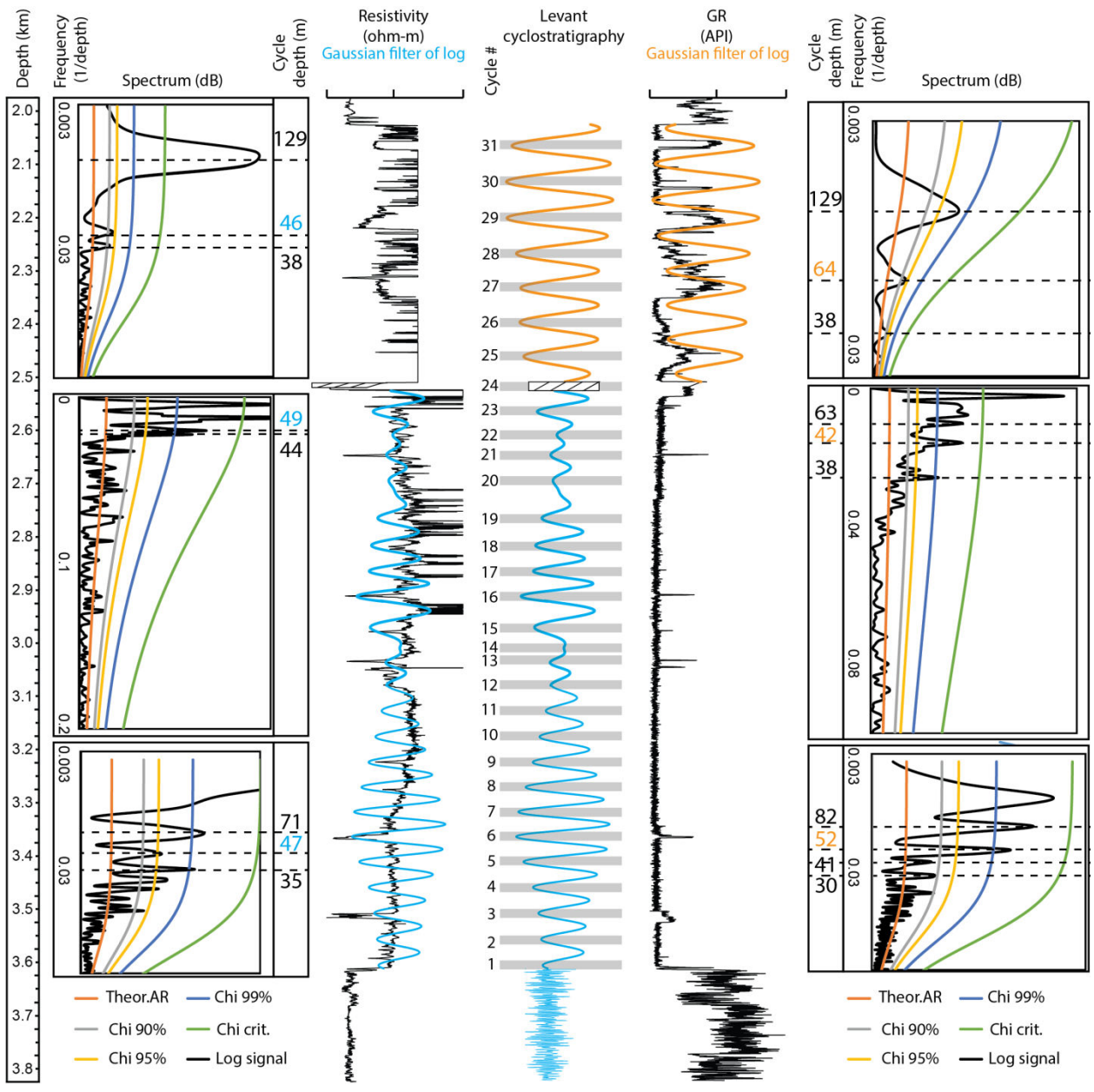
1737 *Figure S1. Strontium stable isotope analysis*

1738 Results obtained by the different protocols used for strontium stable isotope analysis with respect  
1739 to the McArthur et al. (2012) seawater curve. Note the large discrepancies between the results  
1740 obtained by the different methods used, indicating a highly probable contamination from the  
1741 drilling mud used during the retrieval of the halite cuttings samples.

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Figure S2. Spectral analysis of *the Dolphin* well-log curves.

Data shown are the spectral analysis of the resistivity (blue, left) and gamma ray (orange, right) well log curves using REDFIT spectral analysis procedure in Matlab, PAST and Analyseries software. Each log is bounded by respective REDFIT (left of resistivity and right of gamma ray logs) and the combined optimal cyclostratigraphy (center). The REDFIT procedure fits the time series to a red noise model null hypothesis (Theor. AR), produces 'false-alarm' parametric

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1752 approximations (chi<sup>2</sup> of 90%, 95%, and 99%) and a 'critical false-alarm' level (chi crit.). REDFIT  
1753 analyses were run by intervals, defined according to the logs expression as follows: from the  
1754 base to 3175 m, from 3175 to 2560 m, and from 2560 m to the top of the evaporitic bed.

Chronology with a pinch of salt: integrated stratigraphy of Messinian evaporites in the deep Eastern Mediterranean reveals long-lasting halite deposition during Atlantic connectivity

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## Abstract

The Messinian Salinity Crisis (MSC; 5.97-5.33 Ma) is considered ~~to be~~ an extreme environmental event driven by changes in climate and tectonics, which affected global ocean salinity and shaped the biogeochemical composition of the Mediterranean Sea. Yet, after more than 50 years of research, MSC stratigraphy remains controversial. Recent studies agree that the transition from the underlying pre-evaporite sediments to thick halite deposits is conformal in the deep Eastern Mediterranean basin. However, the age of the base and the duration of halite deposition are still unclear. Also disputed is the nature of the intermediate and upper MSC units, which are characterized as periods of increased clastic deposition into the Eastern Mediterranean based on marginal outcrops and seismic data. We provide a multidisciplinary study of sedimentary, geochemical, and geophysical data from industrial offshore wells in the Levant Basin, which recovered a sedimentary record of deep-basin Mediterranean evaporites deposited during the MSC. In combination with previous observations of the MSC throughout the Mediterranean Basin, our results promote the need for a new chronological model. Remarkably, the one-kilometer-thick lower part of the evaporitic unit is composed of essentially pure halite, ~~other than~~except for a thin transitional anhydrite layer at its base. The halite is undisturbed and homogeneous, lacking diverse features apparent in more proximal sections, indicating a deep-sea depositional environment. We ~~confirm~~find that distinct, meters-thick non-evaporitic intervals interbedded with the halite, previously thought to be clastic layers, are indeed diatomites. While XRD analysis confirms an increase in clastic components in these sediments, they are composed

primarily of well-preserved marine and freshwater planktonic diatoms. The occurrence of marine planktonic diatoms in these intervals indicates the input of Atlantic waters into the Mediterranean Basin during the deposition of the massive halite unit. Seismic [stratigraphy](#) and well-log cyclostratigraphy further support deep basin halite deposition, which started about 300 kyr earlier than widely assumed (~5.97 Ma). We propose that halite deposition in the deep Mediterranean took place during stage 1 of the MSC, rather than being limited to the short 50 kyr MSC acme when sea-level was presumably at its lowest. Thus, brine formation, salt precipitation, and faunal extinction occurred at least in part in a deep, non-desiccated basin, with a restricted yet open Mediterranean-Atlantic connection that allowed inflow of oceanic water. We observe an increase in heavy minerals and reworked fauna within the clastic-evaporitic, Interbedded Evaporites of the basal MSC section, and argue that these settings correspond in the deep basins with a significant sea-level drawdown during stage 2 of the MSC, as observed in the marginal sections. This correlation is corroborated by astrochronology and chemostratigraphic markers, such as the distribution of *n*-alkanes and biomarker-based thermal maturity indices.

The Levant deposits indicate that high sea-level and partial connectivity with global oceans promoted the deposition of deep-basin deep-water halite, while sea-level drawdown promoted deposition of reworked and transported material from the margins into deep Mediterranean basins. This [review study](#) modifies the current understanding of the mechanisms governing salt deposition throughout the MSC with implications for other evaporitic events in the geologic record.

*Keywords: Messinian Salinity Crisis, Mediterranean, deep-basin, evaporites, stratigraphy, sedimentology*

## Highlights

- After 50 years of research and over 10,000 publications, Messinian Salinity Crisis chronology is still debated
- We analyze a detailed sedimentary and geophysical record from the deep Levant Messinian halite
- Lithological, stratigraphic, and chemical signals indicate precipitation of halite 300 kyr earlier than presumed
- Halite was deposited in a deep-basin deep-water environment synchronously with gypsum deposition ~~in~~on the margins
- Sea-level drawdown during the MSC acme in the Mediterranean promoted the deposition of reworked material in deep basins

# Chronology with a pinch of salt: integrated stratigraphy of Messinian evaporites in the deep Eastern Mediterranean reveals long-lasting halite deposition during Atlantic connectivity

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## 1. Introduction

An international and multidisciplinary group of scientists have recently joined efforts to organize the challenging endeavor of drilling through the thick Messinian evaporites found in deep Mediterranean basins (IODP pre-Proposal P857B DREAM; Camerlenghi et al., 2014; Lofi and Camerlenghi, 2014). The targeted deep basin evaporites reach up to 3 km in thickness (Hsü, 1973) and are thought to have resulted from restricted connectivity of the Mediterranean Basin to the Atlantic Ocean that led to the Messinian Salinity Crisis (MSC). It has been suggested that deposition of the MSC salt giant has greatly affected the global oceans by sequestering 5% (Ryan, 1973; 2008) to 10% (Garcia-Castellanos and Villaseñor, 2011) of their salt content into the Mediterranean. Also, by contributing warm, saline water to northern latitudes, the MSC influenced Atlantic Meridional Overturning Circulation and, consequently, global climatic shifts (Hernández-Molina et al., 2014). Among the major stratigraphically-driven findings of modern geoscience, the MSC stands alone as being supported by an 'outrageously under-sampled stratigraphic record' (CIESM, 2008). For several decades, focused investigation of the MSC within various interdisciplinary studies was aimed at understanding the mechanisms governing its timing, paleogeography, and the inter-relationship between external forcing and physical systems response. However, while the deep-basin halite was penetrated in its uppermost part (Fig. 1), the prohibitive risk and high drilling cost of recovering cores through the entire deep-basin MSC unit has resulted in a critical lack of data. Scientific drilling of the deep Mediterranean basins has been repeatedly called for in order to test and validate different hypotheses regarding the MSC in the deep Mediterranean basins (CIESM, 2008; Dela Pierre et al., 2014; Gvirtzman et al., 2017; Manzi et al., 2015, 2018; Meilijson et al., 2018), but has yet to be achieved.

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59 24 The MSC came into awareness and was documented as early as the 1950's, when massive  
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61 25 evaporite outcrops in the peri-Mediterranean were identified as co-occurring around the end of  
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63 26 the Miocene (Selli, 1954; Ogniben, 1957). However, the MSC magnitude and extent became  
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65 27 clear only when seismic imaging penetrated the massive diapiric and stratified salt bodies of the  
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67 28 Mediterranean Sea, reaching more than 2 km in thickness and stretching across vast parts of the  
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69 29 basin (e.g., Bourcart et al., 1958; Alinat and Cousteau, 1962; Cornet, 1968; Ryan et al., 1971;  
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71 30 Bellaiche et al. 1974; Ryan, 1976). One of the oldest controversies related to the MSC concerns  
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73 31 the magnitude and timing of sea-level lowering and desiccation, where several models for  
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75 32 evaporite formation have been suggested. Some have proposed that salt was precipitated in deep  
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77 33 basins under a deep-water environment (Schmalz, 1969; Debenedetti, 1982; Sonnenfeld and  
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79 34 Finetti, 2011), while other scenarios promoted a desiccated shallow-water environment (Hsu,  
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81 35 1973). A hybrid model was proposed, with early brine formation in the deep Mediterranean,  
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83 36 preceding substantial drawdown, followed by massive salt precipitation during gateway closure  
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85 37 (Ryan, 2008; Garcia-Castellanos and Villaseñor, 2011; Lofi et al., 2011). Clauzon et al. (1996)  
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87 38 recognized the occurrence of shallow-water first cycle gypsum beds of the same age in many  
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89 39 localities in the western and eastern Mediterranean. Based on this observation they presented a 2-  
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91 40 step model, in which the surface of the Mediterranean Sea remained close to the global ocean  
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93 41 level during the early part of the crisis, and deep-basin evaporites formed following sea-level  
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95 42 drop of the subsequent step. Based on this model, Ryan (2011) described the geodynamic  
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97 43 response of the basin to each of these steps: 1) Significant deepening of the basins by isostatic  
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99 44 load due to an increase in weight of the brine layer. 2) As the basins dried out, the loss of weight  
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101 45 of the water led to regional isostatic uplift that permanently closed the prior inlets.  
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115 46 Van Couvering et al. (1976) were the first to propose a similar 2-step model, which also  
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117 47 portrays an early deposition of halite in the deep basins: (1) An initial deep-water phase marked  
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119 48 by refluxive concentration of brines and controlled by a tectonically elevated sill, during which  
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121 49 evaporites and associated sediments accumulated simultaneously near the surface in marginal  
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123 50 areas (gypsum) and within great saline water bodies in the depths of the basin (halite). (2) A  
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125 51 terminal phase of total isolation, caused by an eustatic sea-level drop, during which erosion and  
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127 52 desiccation features were developed that fit the "deep-basin, shallow-water" model. However,  
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129 53 this model was later abandoned in favor of what developed into the CIESM (2008) workshop  
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131 54 consensus stratigraphic model, which was elaborated in the extensive review of the MSC by  
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133 55 Roveri et al. (2014a) and widely cited.  
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137 56 The CIESM (2008) stratigraphic model of the MSC is based on correlation of Mediterranean  
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139 57 evaporite sequences deposited in marginal to intermediate basins, and their isotopic signatures  
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141 58 (Keogh and Butler, 1999; Müller and Mueller, 1991; Flecker and Ellam, 2006). While the  
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143 59 division of MSC units differs slightly in terminology between the CIESM (2008) model and the  
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145 60 widely used review of the MSC presented by Roveri et al. (2014a), they both stem from the same  
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147 61 stratigraphic concepts, and are jointly referred to here as the 'consensus model' for MSC  
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149 62 chronology. These studies demonstrate that partial connectivity with the Atlantic Ocean persisted  
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151 63 throughout the first phase of gypsum deposition, lasting for ~370 kyr and known as MSC phase  
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153 64 1: Primary Lower Gypsum [PLG], 5.97–5.6 Ma.  
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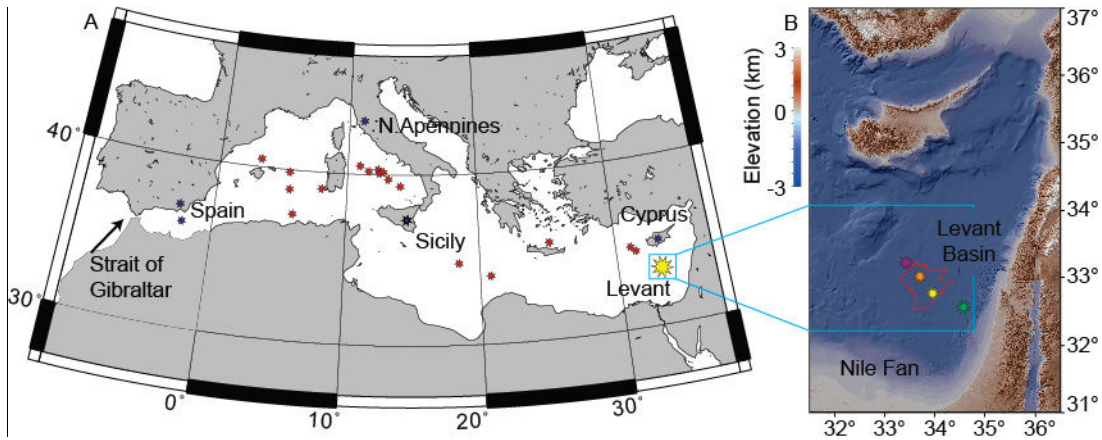


Figure 1. Map of the Mediterranean Sea marking the study area and referenced sections.

**A.** Map of Mediterranean Sea marking study area (yellow star); main referenced sections (blue stars); and Deep Sea Drilling Project and Ocean Drilling Program wells (red stars), which penetrated MSC halite deposits only at their uppermost part. **B.** A shaded relief map of the Levant Basin and surrounding area (Hall et al., 1994, 2015). Red polygon outlines the three-dimensional seismic cube referred to in this study. Well locations marked by stars: Aphrodite-1 (purple star), Leviathan-1 (orange), Dolphin (yellow), and Sara (Green).

During the PLG, euxinic shales and dolostones were thought to have been deposited in the deep basins in parallel to gypsum deposition in the proximal settings (Lange and Krijgsman, 2010). However, using sonic and resistivity logs and samples from cuttings of the 497-Muchamiel oil-industry well, Ochoa et al. (2015) observed all 14 of the known first-stage gypsum beds present in the Sorbas Basin, offshore southeast Spain, deep (875 -965 m) below the present-day sea level. This observation was regarded opposite to previous assumptions that only shales would be present in this interval of the deep basins (CIESM, 2008; Roveri et al., 2014a).

The thick salt unit was interpreted as being accumulated during the succeeding MSC acme, a short period of ~50 kyr known as MSC phase 2: Resedimented Lower Gypsum [RLG], 5.6–5.55 Ma (although its top is often marked at 5.53 Ma in different cyclostratigraphic schemes (e.g., Roveri et al., 2014a; Manzi et al., 2015) due to the ‘Messinian gap’, during which Messinian

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227 85 erosion and/or deposition of resedimented gypsum and halite occurred). A model depicting the  
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229 86 desiccation of the Mediterranean during stage 2 was proposed to explain its formation over such  
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231 87 a short period of time. This model entails a massive sea-level drawdown and consequent removal  
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233 88 and re-deposition of the PLG gypsum, and a seasonal or long-term deposition of halite in  
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235 89 intermediate to deep-water basins. Lastly, the third phase of the MSC was defined within the  
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237 90 Upper Evaporites or Gypsum sequences (UG), which include clastic or brackish sediments  
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239 91 culminating in the Lago-Mare deposits (5.55-5.33 Ma). The latter consist of several units with 7-  
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241 92 10 sedimentary cycles identified in the Upper Gypsum of Italy overlying erosional surfaces and  
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243 93 angular unconformities, and underlying Pliocene sediments (Hilgen et al., 2007; Krijgsman et al.,  
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245 94 2010; Roveri et al., 2014a). A recent review of different Lago-Mare deposits depicts that three  
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247 95 main pulses of seaward-transport occurred within the time-interval 5.64-5.33 Ma, and suggests  
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249 96 abandonment of previous concepts dealing with a unique chronostratigraphic unit, favoring  
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251 97 several episodes of flooding (Couto et al., 2014). Nonetheless, the first influx of Paratethyan  
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253 98 organisms, identified through the dinoflagellate cyst record near Malaga within a fan delta, was  
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255 99 found overlying the intra-Messinian truncation surface (IMTS) (Couto et al., 2014).

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259 100 Recent industrial activities targeting hydrocarbon reservoirs in the Eastern Mediterranean  
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261 101 Basin provide the scientific community with unparalleled seismics, well logs, and cuttings across  
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263 102 the salt interval. The current work takes advantage of these industrial data to address two critical  
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265 103 issues regarding Messinian stratigraphy in the deep Eastern Mediterranean Basin, which impact  
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267 104 our basic understanding of this event: (1) To evaluate the composition, age and duration of  
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269 105 evaporite deposition in the Eastern Mediterranean. (2) To characterize, interpret, and  
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271 106 stratigraphically position the sediments overlying the IMTS (as in Gvirtzman et al., 2017),  
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273 107 termed here the Interbedded and Argillaceous Evaporites. Here, we report previously unknown  
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108 features and lithology of the deep basin MSC and, by using a multi-disciplinary approach, we  
109 provide further interpretation of their stratigraphy.

## 110 **2. MSC deposits in the Levant**

111 Feng et al. (2016) analyzed jointly well-log measurements and a pervasive seismic dataset,  
112 and demonstrated that the seismically transparent layers composing the majority of the  
113 Messinian evaporite deposits across the deep Levant Basin are composed of pure halite. The  
114 reflective layers appearing within the halite (Figs 2, 3) were interpreted as bundles of thin clay  
115 layers interbedded in the halite background, having a cumulative thickness of 25-40 m. Feng et  
116 al. (2016) also reported high-amplitude fan structures on the deepest internal reflectors, which  
117 may suggest transport mechanisms. Later, Gvirtzman et al. (2017) argued against a complete  
118 desiccation of the Eastern Mediterranean, following the seismic identification of the IMTS at  
119 ~100 m below the Messinian-Zanclean boundary in the Levant Basin. Based on interpretation of  
120 well logs and correlation to shallower-water wells, Gvirtzman et al. (2017) suggested that the  
121 post-truncation Messinian unit is different from the underlying salt deposits and mostly consists  
122 of shale, sand and anhydrite. Lastly, two separate studies (Manzi et al., 2018; Meilijson et al.,  
123 2018) have investigated the sediments underlying the evaporites, based on data from different  
124 wells within the Levant Basin. Both studies address the stratigraphy of the Pre-Evaporites and  
125 are aimed at providing an indication for the age of the base of the halite in the deep Eastern  
126 Mediterranean, represented on seismic data in the region as the ‘N’ reflection (Ryan, 1978;  
127 Bertoni and Cartwright, 2007). Establishing the age and duration of the deep-basin halite is  
128 perhaps the most enigmatic aspect of MSC research. Both recent studies test the CIESM  
129 stratigraphic model of the MSC (CIESM, 2008; Dela Pierre et al., 2014; Roveri et al., 2014a).



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339 130 Manzi et al. (2018) and Meilijson et al. (2018) report several similar findings, such as the  
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341 131 seismic interpretations regarding the conformity of the base of the evaporites, and thus refuting  
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343 132 the occurrence of a long hiatus at the base of the evaporites. In addition, both studies indicate  
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345 133 little deformation of the Levant Pre-Evaporite interval and a continuous record of the Tortonian  
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347 134 to Messinian sediments. Still, different observations reported in these studies have led to  
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349 135 continued uncertainty concerning the age and duration of salt deposition.  
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351  
352 136 Meilijson et al. (2018) considered two alternatives for the age of the base evaporites in the  
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354 137 deep basins: (1) during stage 1 (PLG) of the MSC at around 5.9 Ma, or (2) at around 5.6 Ma  
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356 138 during stage 2 (RLG) of the MSC, as is described in the CIESM stratigraphic model (CIESM,  
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358 139 2008; Roveri et al., 2014a). The latter would imply a major hiatus of ~370 kyr (missing the PLG  
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361 140 equivalent unit) at the base of the salt, or alternatively that the PLG is expressed as a very thin  
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363 141 interval in the uppermost Pre-Evaporites unit. A hiatus in the deep basin has not been identified,  
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365 142 but rather a visible lateral continuity of seismic reflectors below and at the boundary itself  
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367 143 (Meilijson et al., 2018). This finding is consistent with published regional seismic sections (Feng  
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369 144 et al., 2016; Manzi et al., 2018; Roberts and Peace, 2007) and elsewhere in the deep domain of  
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371 145 the Mediterranean (Lofi et al., 2011). Thus, Meilijson et al. (2018) concluded that the studied  
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373 146 section is in fact conformal and halite began to precipitate around the onset of the PLG in the  
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375 147 marginal basins, predating the CIESM consensus for halite deposition by ~300 kyr.  
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377  
378 148 Manzi et al. (2018) reported that in the Aphrodite-2 well (Fig. 1), which is the deepest  
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380 149 location along their four-well cross-section, a complete absence of foraminifera occurs from  
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382 150 3959 m upwards, 28 m below the first occurrence of anhydrite, and 33 m from the base of halite  
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384 151 deposition. They interpret this foraminifera barren interval (FBI) as corresponding to the Non-  
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386 152 Distinctive Zone (NDZ) marking the onset of the MSC (5.971 Ma) in marginal settings (Gennari et  
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153 al., 2013; Manzi et al., 2013). Manzi et al. (2018) proposed that this interval represents the deep basin  
154 expression of the PLG, followed by halite deposition during stage 2 of the MSC at around 5.6 Ma.  
155 This FBI is argued by them to be further substantiated by a prominent peak of *Sphenolitus abies* at  
156 3961 m, closely followed by a decrease in the number of species of calcareous nannofossils. The  
157 FBI was also identified by Manzi et al. (2018) in the Myra well, which is situated in a more proximal  
158 position, 90 km SW to the Aphrodite well. Farther landward to the west, the FBI is no longer  
159 recognized in the Sara well, where the Aphrodite well equivalence of about 60 m underlying the base  
160 of the evaporites is missing. This observation indicates that the Dolphin well should also include an  
161 equivalent FBI, as it is positioned between the Myra well, and closer to the latter (Fig. 1). However,  
162 such an FBI is not present in the Dolphin well, in which the samples include a relatively open-marine  
163 foraminiferal assemblage up to the uppermost sample available for analysis, representing the interval  
164 0-9 m below the base of the evaporites (Meilijson et al., 2018). Thus, the MSC timing and events are  
165 still debated after more than 50 years of research and over 10,000 publications.

166 In recent years, different studies have been leaning towards new and very different ideas  
167 regarding MSC chronology, and thus the mechanisms controlling the deposition of salt giants in deep  
168 sea basins. Ochoa et al. (2015) demonstrated synchronous deposition of evaporites in marginal and  
169 intermediate basins. Simon and Meijer (2017) modeled stratification in the Mediterranean during the  
170 MSC and raised the possibility of a much earlier onset of halite in the deep basins. Finally, García-  
171 Veigas et al. (2018) even went so far as to draw a model for an early onset of halite, yet added a  
172 question mark next to this assumption due to lack of proof for this claim (their fig. 12). Here, we  
173 address this debate on the chronology of MSC events in the Mediterranean by examining the  
174 recovery of deep-basin evaporites from the Levant Basin for stratigraphic indicators that can promote  
175 a better understanding of MSC chronology.

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451 176 The MSC (CIESM, 2008; Roveri et al., 2014a) is expressed in the southeastern Levant Basin  
452  
453 177 margins as a thick evaporitic sequence (locally named the Mavqiim Formation), as well as clastic  
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455 178 evaporite deposits along local topographical lows (Buchbinder and Zilberman, 1997; Druckman  
456  
457 179 et al., 1995; Lugli et al., 2013). The MSC deposits in the deep Levant Basin have been identified  
458  
459 180 through seismic data, and interpreted as mainly consisting of halite, reaching a thickness of  
460  
461 181 ~2 km in the central part of the basin and pinching out upslope towards its southeastern margin  
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463 182 (Bertoni and Cartwright, 2007, 2006; Feng et al., 2016; Gardosh et al., 2008; Netzeband et al.,  
464  
465 183 2006; Steinberg et al., 2011). The halite sequence base and top are generally imaged as  
466  
467 184 pronounced high-amplitude seismic reflections, known as the N and M reflectors, respectively  
468  
469 185 (Ryan, 1978). Up-dip, the evaporitic sequence thins below seismic resolution and is entirely  
470  
471 186 represented by the M reflector (e.g., Steinberg et al., 2010). The nomenclature of the MSC  
472  
473 187 section in the Levant Basin is currently based on the regional identification of a number of key  
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475 188 markers within seismic sections across the basin, with several divisions presented by different  
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477 189 studies: division of the section into 6 or 7 units (Gvirtzman et al., 2013b, 2017; Lugli et al.,  
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479 190 2013), or into ME 1-4 (Messinian evaporites) and MC 1 and 2 (Messinian clastics; Feng et al.,  
480  
481 191 2016). In this manuscript we refer to the unit numbers (Gvirtzman et al., 2017, 2013b) and  
482  
483 192 ME/MC units (Feng et al., 2016), corresponding seismically to the lithostratigraphic descriptions  
484  
485 193 and division of the Dolphin well sediments.

489 194 Several studies have shown that the seismic records of the MSC greatly differ between the  
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491 195 Western and Eastern Mediterranean basins, and argued that it is impossible to properly correlate  
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493 196 individual sub-units (Lofi et al., 2011). Some authors have also questioned the possible  
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495 197 diachronism between both basins (Blanc, 2000; Ryan, 2008). However, the Levant has been for  
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497 198 many years at the center of debate regarding the evolution of the MSC across the entire  
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199 Mediterranean Basin. An example for such a long-term debate includes the formation of the vast  
200 drainage systems at the Mediterranean margins and the deposition, or re-deposition, of gypsum  
201 within them. An important type location for this debate is the Afiq canyon along the continental  
202 margin of Israel. The presence of evaporite layers at different levels along the Afiq canyon was  
203 brought as one of the first evidence for a substantial Messinian sea-level drawdown (800 m sea-  
204 level drop; Druckman et al., 1995). However, these deposits were recently argued to result from  
205 evaporite recycling through slope mass-wasting, a phenomena suggested to characterize the  
206 upper parts of the MSC throughout the Mediterranean (Lugli et al., 2013). The wells investigated  
207 in this study were drilled in the Levant Basin, and may represent local conditions rather than  
208 account for the entire Mediterranean Basin. However, by recovering one of the most extensive  
209 evaporite deposits of the MSC, the analysis of these wells bears key implications for unraveling  
210 the MSC across the entire Mediterranean.

### 211 **3. Methodology**

212 This study is based on the combined analyses of well cuttings, 3D pre-stack depth-migrated  
213 reflection seismics, and well-log data of two deep-water industry wells recently drilled in the  
214 Levant Basin (Fig. 1). We have also used a time-migrated 2-D seismic survey acquired by TGS-  
215 Nopec Geophysical Company in 2000, and the 3-D depth-migrated Pelagic seismic survey  
216 acquired by CGG-Veritas in 2009. Lithological and biostratigraphic data presented in this study  
217 are from the Dolphin well (N 3628144.05 m, E 575444.97 m), drilled by the Leviathan  
218 partnership at a water depth of 1500 m and penetrating the 1590 m thick Messinian evaporite  
219 section at depths of 2026-3616 m below sea level. The second studied well is the Leviathan-1 (N  
220 3653455.35 m, E 553663.40 m), also drilled by the Leviathan partnership at a water depth of  
221 1644 m and penetrating the 1694 m thick Messinian evaporite section at depths of 2090-3784 m

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563 222 below sea level. The record presented in this study supplements the 350 m section immediately  
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565 223 below the base of the halite shown in Meilijson et al. (2018). Samples were curated and archived  
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567 224 in both the Organic Geochemistry Laboratory at the University of Colorado (organic extracts)  
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569 225 and the Department of Marine Geosciences, Leon Charney School of Marine Sciences,  
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572 226 University of Haifa.

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574 227 Drilled cutting returns are available starting down from a depth of 2535 m and 2497 m in the  
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576 228 Dolphin and Leviathan-1 wells, respectively. The Pre-Evaporites interval of the Dolphin  
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578 229 (Meilijson et al., 2018) and Leviathan wells was sampled every 3 m. The evaporite interval was  
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580 230 sampled every ~9 m, with a total of 123 samples from the Dolphin well. Due to standard drilling  
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582 231 activities, many fallouts of clastic deposits occur downhole from the lower part of the  
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584 232 Interbedded Evaporite unit to the upper part of the Main Halite unit, appearing as an interval of  
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586 233 clastic deposits in the XRD log of the Dolphin well from 2560 to 2675 m. Well-log data does not  
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588 234 respond to this high-clastic content (i.e., high RE log values and low GR log values), and so does  
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590 235 not show a shift from halite deposition. This observation confirms that the clastic material arrive  
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592 236 from the unit above, as drilling fallouts into the halite interval. While not in-situ, these fallouts,  
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594 237 together with the well logs, allow us to interpret the distinct lithological transition that occurs at  
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596 238 the boundary between the Main Halite and Interbedded Evaporites unit. However, these fallouts  
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598 239 might also originate from the Argillaceous Evaporites unit above.

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601 240 Individual cutting bits were separated by their lithology under a microscope, cleaned with  
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603 241 deionized water and 10% hydrochloric acid, dried, and then crushed in an agate pestle and  
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605 242 mortar. Fine powders were pressed and used for bulk mineralogical X-ray diffractogram (XRD)  
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607 243 analysis using a Rigaku 600 MiniFlex X-Ray Diffractometer with a CuK $\alpha$  source at 30kV / 15-  
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609 244 mA from 3° to 70°. Mineralogical compositions of assemblages were determined using the  
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619 245 ICDD PDF2 mineral database references. Next, fine powders were pressed in Teflon crucibles  
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621 246 with X-Ray transparent mylar (which was replaced between samples). Each sample was then  
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623 247 analyzed using a Nitton X-Ray XL3 GOLDD+ Fluorescence apparatus for elemental  
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626 248 composition.

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628 249 Samples found to be bearing microfossils were investigated for their faunal assemblages,  
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630 250 which included washing and picking foraminifera from the Pre-Evaporites (detailed in Meilijson  
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632 251 et al., 2018) and the preparation of smear slides for the study of the diatomites interbedded  
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634 252 within the halite. For the latter, samples were weighed, treated several times with 10% HCl for  
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636 253 carbonate removal, and 30% hydrogen peroxide for organic matter removal, and then loaded  
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638 254 onto glass slides. A total of 50 diatom valves were counted and identified from 10 samples.  
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640 255 Diatoms were characterized by their habitat preferences: planktonic vs. benthic, and marine vs.  
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642 256 freshwater.

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645 257 We also studied the distribution of selected biomarkers (i.e., *n*-alkanes, algal steranes, and  
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647 258 bacterial hopanes) from different intervals to gain insight into variations in organic matter  
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649 259 sources and thermal alteration. Rock cuttings were cleaned and handled with solvent-rinsed  
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651 260 metal tweezers, a Dremmel 8220 wire-brush tip, spatulas, and combusted aluminum foil, and  
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653 261 then powdered with a solvent-rinsed agate mortar and pestle. Approximately 5-10 grams of  
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655 262 sample were extracted using a Dionex Accelerated Solvent Extractor (ASE 200; 100 °C; 2,000  
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657 263 psi) and a mixture of dichloromethylene:methanol 9:1 (v:v) until no more color was observed  
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659 264 (typically 3-6 extractions). Each extraction cycle included heating of the cell for 5 minutes, static  
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661 265 mode for 5 minutes, and flushing for 2 minutes time. A cocktail of internal standards containing  
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663 266 500 ng of D4 C<sub>29</sub> ααα (20R)-Ethylcholestane, and 1,000 ng of each 3methyl heneicosane, D14  
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665 267 pTerphenyl, 1-nonadecanol, behenic acid methylester (Docosanoic acid), and 2methyl  
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675 268 octadecaonic acid, was added to samples before extraction for quantitation purposes. Total lipid  
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677 269 extracts (TLEs) were combined and evaporated under a gentle nitrogen flow using a Turbovap.  
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679 270 Elemental sulfur was removed using HCl-activated copper shots. TLEs were then filtered  
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681 271 through small Pasteur pipettes filled with combusted glass wool and sand to remove impurities  
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683 272 and any copper-sulfide residues. Asphaltenes were separated from maltenes by precipitation in  
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685 273 hexanes at 4<sup>0</sup>C for 3 hours, followed by centrifugation at 2000 rpm (3x). Maltenes were later  
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687 274 separated into five different lipid classes by liquid chromatography on small Pasteur pipettes  
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689 275 filled with silica gel. Aliphatic (F1) and aromatic (F2) hydrocarbons were recovered with hexane  
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691 276 (3/4 dead volumes) and hexane:dichloromethylene 8:2 (v:v; 4 dead volumes), respectively. The  
692  
693 277 more polar fractions (F3, F4, F5) were eluted using dichloromethylene,  
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695 278 dichloromethylene:EtOAc 1:1, and EtOAc (v:v, 4 dead volumes), respectively. Aliphatic  
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697 279 hydrocarbons were analyzed on full scan and selected reaction monitoring (SRM) modes via gas  
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699 280 chromatography – triple quadrupole-mass spectrometry (GC-QQQ-MS) using a Thermo Trace  
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701 281 1310 Gas Chromatograph interfaced to a TSQ Evo 8000 triple quadrupole mass spectrometer  
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703 282 (GC-QQQ-MS) equipped with a split-less PTV injector and electron impact ion source. Helium  
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705 283 was used as a carrier gas with a flow rate of 1.2 ml min<sup>-1</sup>. Chromeleon 7 was used for data  
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707 284 integration. Aliphatic hydrocarbons were separated using a 60-meter DB-1MS GC column (60  
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709 285 m, 0.25 mm I.D., 0.25 μm film thickness; Agilent Technologies). For FS analysis, samples were  
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711 286 injected at 60°C and then the PTV was heated to 300°C at 14.5°C/second. The GC oven  
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713 287 temperature program was: 60°C (2 min) to 150°C at 15°C min<sup>-1</sup>, to 315 (held 24 min) at 3°C  
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715 288 min<sup>-1</sup>. The total GC program was 90 minutes. MS conditions were: 300°C ion source at 70eV  
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717 289 electron energy, 50uA emission current, and 15V electron lens voltage. The mass range was 50-  
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719 290 600 m/z with a dwell time of 0.2 seconds per scan. For SRM analysis, the GC oven temperature  
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731 291 program was: 60°C (0 min) to 220°C at 15°C min<sup>-1</sup>, to 315°C (held 25 min) at 3°C min<sup>-1</sup>. The  
732  
733 292 total GC program was 68 minutes. Samples were injected at 65°C and then the PTV temperature  
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735 293 was heated to 400°C at 3 °C min<sup>-1</sup>. MS conditions were: ion source temperature of 250°C;  
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737 294 transfer line temperature of 320°C, electron energy of 70eV, electron lens voltage of 35V, and  
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739 295 emission current of 35uA. Peak scanning windows ranged from 0.6 to 1 minute for 147 timed  
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741 296 transitions for regular and methylated steranes and hopanes, and their stereoisomers.  
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## 744 297 **4. Evidence from the Levant Basin for an early onset of halite deposition in a deep-water** 745 746 298 **environment**

### 749 299 **4.1 Lithologic composition of the Levant deep-sea salt-giant**

#### 752 300 *4.1.1 Pre-Evaporites*

754 301 This interval is detailed in Meilijson et al. (2018). Here we provide a generalized summary,  
755  
756 302 followed by a more elaborate account of the overlying evaporites of the deep Levant Basin. The  
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758 303 Pre-Evaporite interval in the Dolphin well (3850-3616 m; Fig. 2) is seismically characterized by  
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760 304 sub-horizontal and sub-parallel continuous high-amplitude reflections, implying a stratified and  
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762 305 relatively undeformed marine succession (Meilijson et al., 2018). It is composed of fine-grained  
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764 306 clastic-micritic and carbonate bathypelagic sediments, primarily gray to dark gray or greenish  
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766 307 calcareous soft to hard shale, with several thin layers of white to light gray hard limestone, and  
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768 308 light gray very fine to fine-grained unconsolidated sandstone. Diverse assemblages of  
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770 309 nannofossils, benthic and planktic foraminifera are recognized within this interval.  
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775 311 *Figure 2. The MSC succession of the Dolphin well in the deep Levant Basin.*

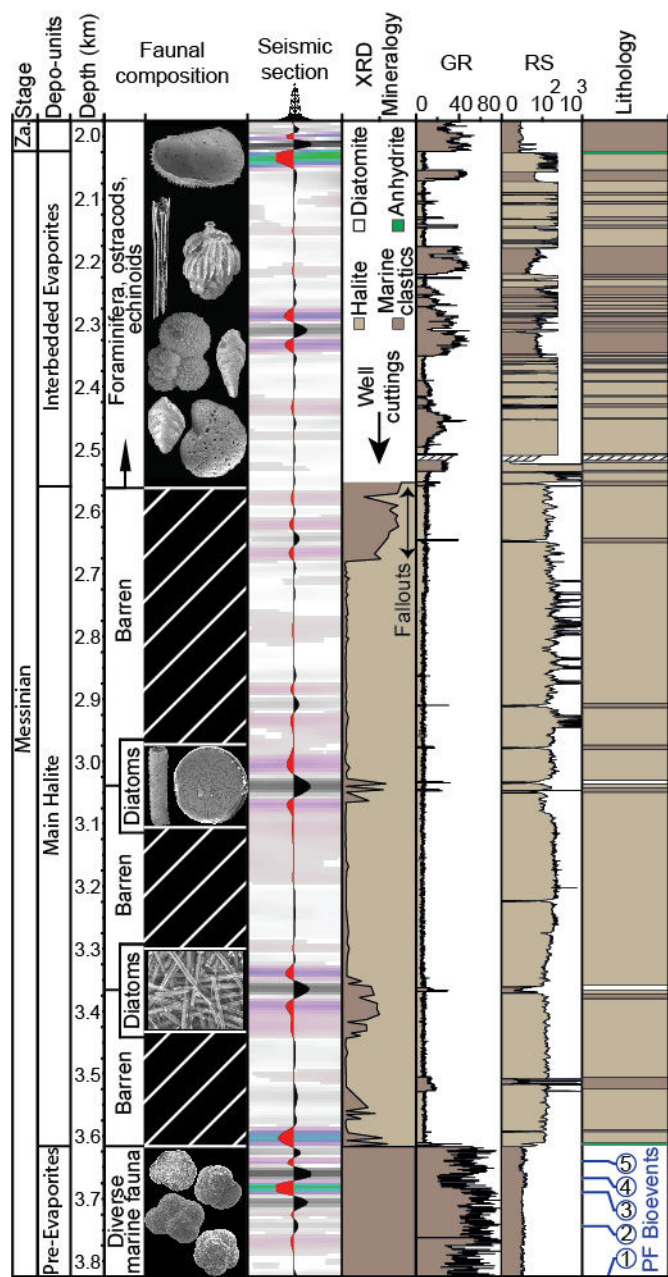
776 312 A juxtaposed simplified display of the primary proxies used to characterize the Dolphin well  
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778 313 section (five central columns), and our depositional (left) and lithological (right) interpretations.  
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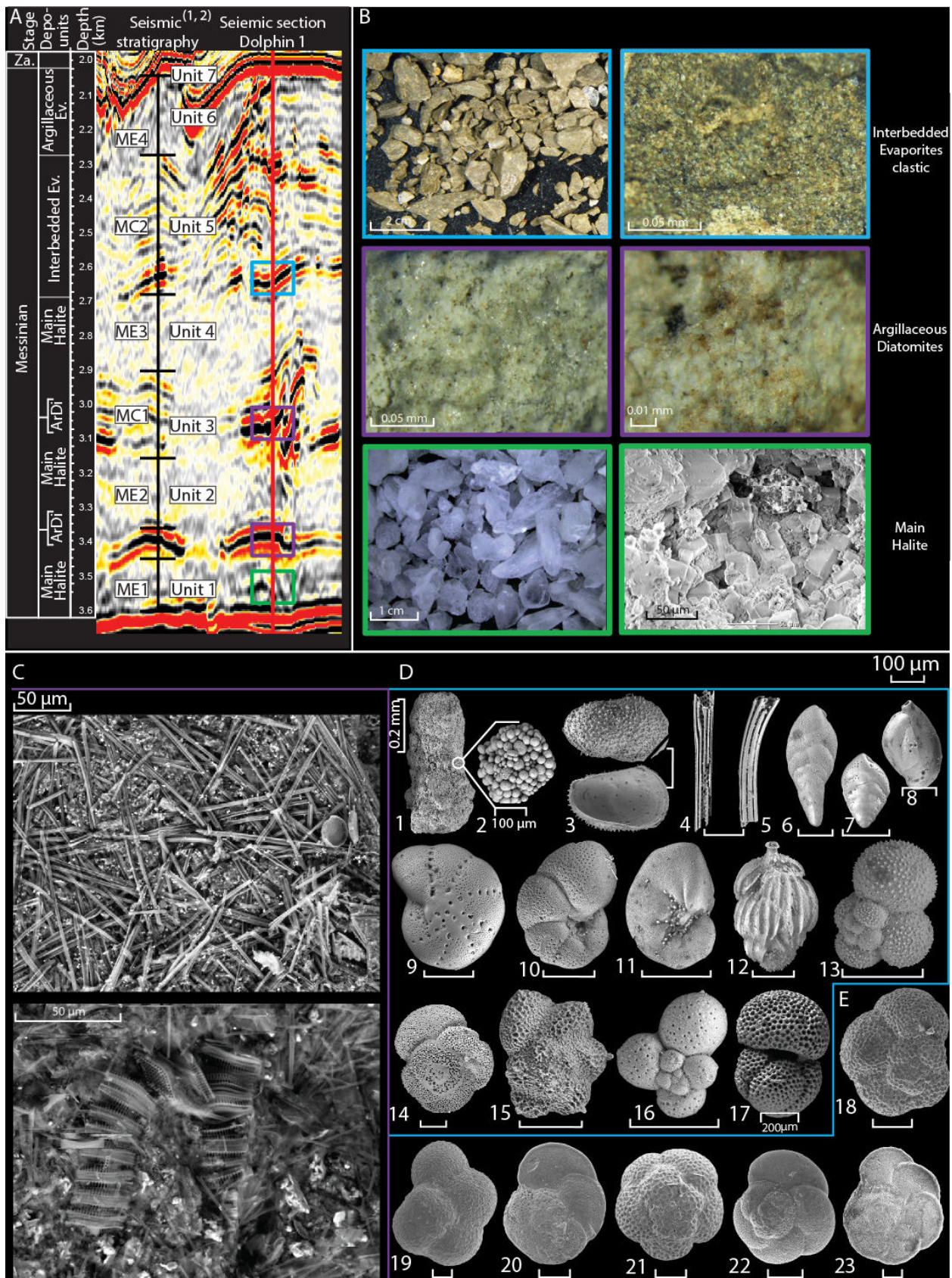
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787 314 The attributes are (left to right): the faunal composition; the seismic response, with transparent  
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789 315 intervals representing predominantly evaporites and high-amplitude reflections representing  
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791 316 clastic beds (a seismic trace (center) emphasizes relative intensity of the seismic phases); XRD  
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793 317 mineralogy, showing the relative abundance of halite (bright) vs. non-halite (dark; 'marine  
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795 318 clastics'), where the uppermost clastic interval (<2650 m) represents fallouts from the  
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797 319 Interbedded Evaporites; the gamma ray (GR - API units) and resistivity (RE - log ohm-m units)  
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799 320 logs, color coded based on the characteristic responses to halite and clastics. The lithological  
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801 321 interpretation is color coded as in the attribute columns. Planktonic foraminiferal (PF) bio-events  
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803 322 in blue circles correspond to the following ages: 1- 7.72, 2- 7.24, 3- 6.72, 4- 6.36, and 5- 6.13 Ma  
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805 323 (Meilijson et al., 2018).  
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955 327 *Figure 3. Seismic stratigraphy, common lithologies, and SEM imaging of the studied section.*  
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957 328 **A.** The seismic profile crossing the sampled Dolphin well position and its division into the MSC  
958 329 depositional units, compared to previously published seismic stratigraphy of the deep Levant  
959 330 MSC ((1) Feng et al., 2016; (2) Gvirtzman et al., 2017). ArDi - Argillaceous Diatomites; Ev. -  
960 331 Evaporites. Color coded rectangles corresponding to lithologies described in (B). **B.** images of  
961 332 the three main facies recognized in the Levant evaporite section: the homogeneous Main Halite  
962 333 (green rectangle) made of pure halite as seen in hand specimen (left) and SEM imagery of cubic  
963 334 cleavage (right), corresponding with subdued internal seismic reflectivity in (A); Argillaceous  
964 335 Diatomite beds (purple rectangle), represented by high amplitude reflections in (A); and  
965 336 Interbedded Evaporites (blue rectangle) identified as brown marine clastics, characterized by  
966 337 interchanging low and high amplitude reflections in (A). **C.** Selected SEM images from the  
967 338 densely packed and very well preserved diatoms from the diatomite facies. **D.** Selected SEM  
968 339 images of the >63 µm size fraction of the washed residue from the Interbedded Evaporites unit  
969 340 clastic sediments (P.1-17) showing: large grains of framboidal pyrite (P.1-2), well-preserved  
970 341 ostracod valves (P.3), sea urchin spines (P.4-5), benthic foraminifera (P.6-12), and planktic  
971 342 foraminifera (P.13-17). **E.** SEM images of the planktic foraminifera used for the biostratigraphic  
972 343 age model (Meilijson et al., 2018) of the Pre-Evaporites (P.18-23): *Neogloboquadrina* sp. (P.18),  
973 344 *Sphaeroidinellopsis seminulina* (P.19), *Globorotalia miotumida* (P.20), *Globoquadrina altispira*  
974 345 (P.21), *Globorotalia scitula* (P.22); *Globorotalia menardii*-4 (P.23). All scales are 100 µm unless  
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989 348 Shale samples are organic-rich (>1 wt.% TOC) and reach peak values of 4 wt.% TOC  
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991 349 immediately underlying the base of evaporite deposition (Meilijson et al., 2018). Lower values of  
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993 350 gamma ray (GR) are associated with silt/carbonate-rich sediments, while higher GR corresponds  
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995 351 to shale/organic-rich sediments (Fig. 2).  
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#### 998 352 *4.1.2 Main Halite*

1000 353 Here we reference our lithologic interpretation to the recently defined seismic stratigraphy of  
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1002 354 the Levant MSC (Units 1-6; Gvirtzman et al., 2013), and ME1-4 for the transparent and MC1-2  
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1011 355 for the high reflectivity intervals (Feng et al., 2016) (Fig. 3). Different velocity models reported  
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1013 356 high seismic velocities of 4200-4400 m/s (Gvirtzman et al., 2013a), 3850-4240 m/s (Reiche et  
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1015 357 al., 2014), and 4400-4600 m/s (Feng et al., 2016) for the seismic transparent layers, interpreted  
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1018 358 as representing the halite facies. Here we advocate this interpretation by providing the first semi-  
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1020 359 quantitative XRD analysis (Fig. 4) of well cuttings spanning the transparent high velocity layers.  
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1022 360 The Main Halite unit in the vicinity of the Dolphin (3616- 2755 m) and Leviathan-1 (3759-  
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1024 361 2800 m) wells is characterized by low seismic reflectivity, which is internally interrupted by  
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1026 362 several main high reflectivity bands (Figs 5, 6). These instances are clearly recognized in the  
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1028 363 well logs (Fig 2, 5), and represent a different facies within the hypersaline deposits described  
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1030 364 below. Using XRD analysis coupled with SEM (Fig. 4), we conclude that the transparent  
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1032  
1033 365 intervals are indeed composed of nearly pure (>90%) halite (Fig. 4), with minor quantities of  
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1035 366 anhydrite, magnesite and barite. Anhydrite is also present as a relatively thin bed (<3 m) at the  
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1037 367 base of the Main Halite section, where it represents the transition to the Main Halite. Anhydrite  
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1039 368 further appears in the upper, more elastic part of the section (Fig. 2), as is also reported from the  
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1041 369 same stratigraphic interval by Gvirtzman et al. (2017). The halite is clear to milky white with a  
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1043 370 firm to very hard macrocrystalline structure (Fig. 3), while the anhydrite minerals are white, soft  
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1045 371 to firm, nodular and amorphous to massive. A sharp transition from the Pre-Evaporites to halite  
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1047 372 is marked by a decrease in GR well log counts from 53 API to 12 API as well as a sharp increase  
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1049 373 in the RE well log reaching 10,000 ohm (Fig. 2; see also Feng et al., 2016).  
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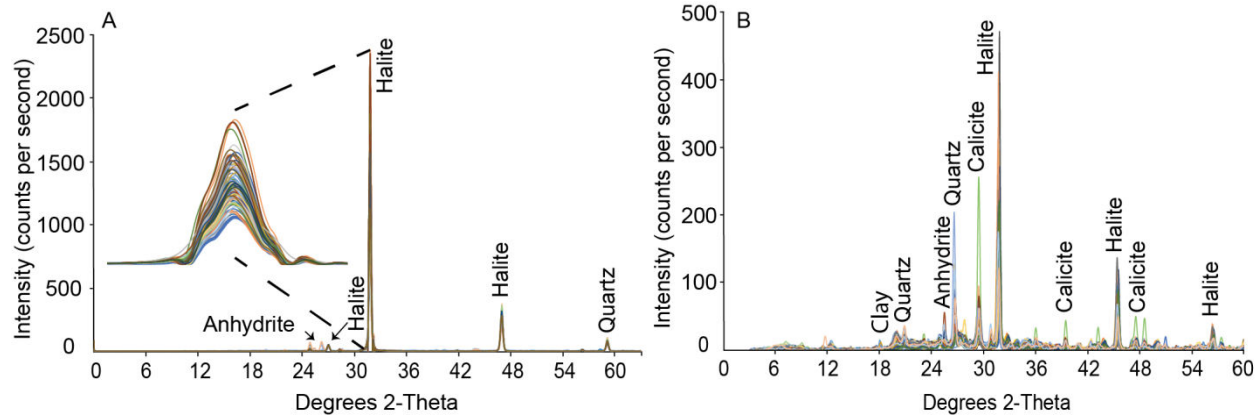


Figure 4. X-ray diffraction results

**A.** Overlaid (color coded) XRD analysis of 89 halite samples from the Dolphin well produced diffractograms, which are practically identical. The main halite peak is zoomed for emphasis. **B.** Higher variability is recorded both in peak location and intensity when analyzing samples from the non-evaporitic marine sediments, sampled along the section between the depth of 3,616 m to 2560 m.

These values remain relatively constant within the halite deposits, although inter-halite variations are observed, mainly on the RE log. The pronounced high-amplitude reflection at ca. 3520 m (Dolphin well; Figs 2, 3), also recognized as an increase in the GR well logs, represents a short-term return to the clastic Pre-Evaporites facies although with low abundance and poorly preserved foraminiferal content. This interval is not part of the Argillaceous Diatomites facies.

#### 4.1.3 Argillaceous Diatomites

Distinct reflective layers appear within the seismic transparent halite expressions, correlating with relatively lower velocity zones in the seismic velocity models developed for the deep Levant Basin MSC strata (e.g., 3800-4000 m/s in Gvirtzman et al. (2013); 3650-4030 m/s in Reiche et al. (2014)). These reflective layers are easily identified across the study area (Figs 5, 6).

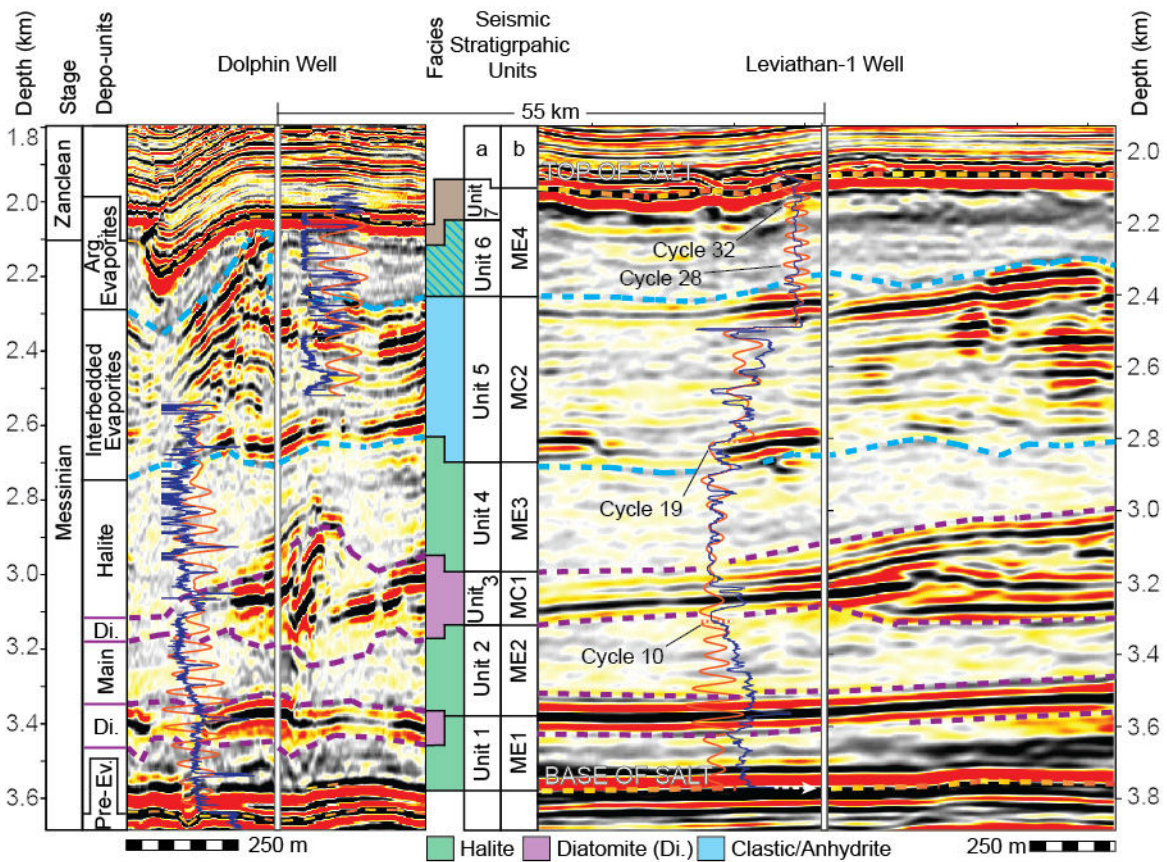
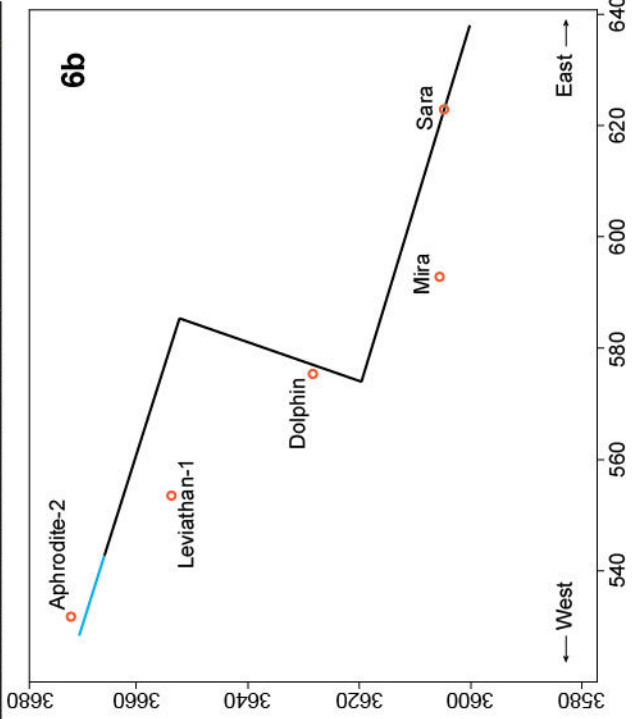
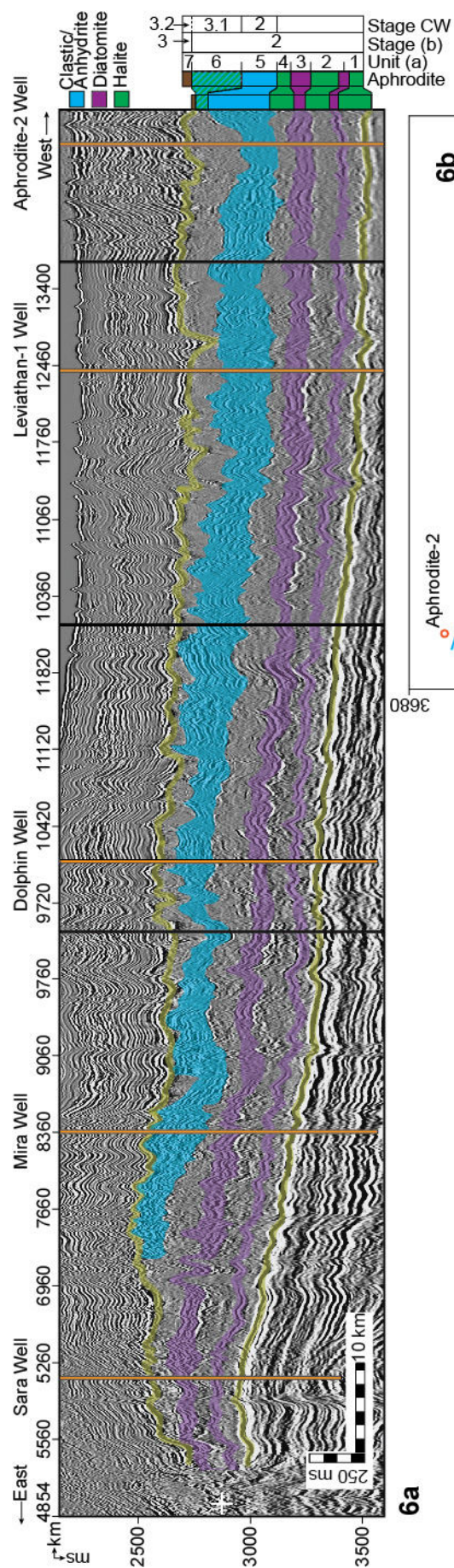


Figure 5. Geophysical data and seismic stratigraphy of the Dolphin and Leviathan-1 wells. Depth-migrated sections crossing the Dolphin (left) and Leviathan-1 (right) wells (marked by a vertical white line). Overlaid on the sections are the well logs (blue curve left to the well), and the filtered well-log cycles superimposed on the target curves (orange). The depth and lithostratigraphic units (this work) related with the sampled Dolphin well are displayed on the left, and the depth related with the Leviathan-1 well is displayed on the right. Data columns in the middle are seismic-stratigraphic units from (a) Gvirtzman et al. (2013, 2017), and (b) Feng et al. (2016). Note the relatively deformed area of the Dolphin well relative to the more conformal vicinity of the Leviathan-1 well.

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1235 404 *Figure 6. A composite seismic section linking the commercial wells across the Levant Basin.*  
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1237 405 A composite time-migrated seismic section (a), and location map (b), combining three 2D  
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1239 406 traverses of the TGS survey (dark line) with a transect through the Pelagic 3D volume (blue line)  
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1241 407 across the Levant Basin, all plotted at a common scale with a vertical exaggeration of ca. x10.  
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1243 408 Orange vertical lines note the positions of the wells discussed in the text, while black lines note  
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1245 409 the section stiches, primarily at turning points. The wells are projected laterally onto the seismic  
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1247 410 profiles by up to 10 km (in the case of the Leviathan-1 well). Note the similar relative spatial  
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1249 411 thickness of the diatomite beds (purple) in comparison with the largely varying thickness of the  
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1251 412 Interbedded Evaporites (blue). Stage CW (current work); Stage (b) (Manzi et al., 2018); Unit (a)  
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1253 413 (Gvirtzman et al., 2013; 2017).  
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1258 415 In the Dolphin well, this seismic facies includes five seismic high-reflectivity bands,  
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1260 416 corresponding to peaks in the GR and troughs in the RE well logs, appearing within the Main  
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1262 417 Halite interval between 3375 and 2560 m (Fig. 2). Using a GR value of 20 API as an upper  
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1264 418 cutoff value for determining the location and thickness of these intervals results in estimated bed  
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1266 419 thicknesses of 0.9-2.4 m (Fig. 2). Of the 1,056 m Main Halite interval in the Dolphin well, the  
1267  
1268 420 non-halite sediments form a regional cumulative thickness of 25-40 m (see also Feng et al.,  
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1270 421 2016; Gvirtzman et al., 2013). At the macro-scale, the content of these layers appears as light  
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1272 422 gray to white, soft to firm, porous, and occasionally fibrous. SEM imaging and smear-slide  
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1274 423 analyses indicate that the rock-mass is made of densely packed, very well-preserved, and intact  
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1276 424 diatoms (Fig. 3), and fine-grained terrigenous sediments (Fig. 4). No other transported or local  
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1278 425 faunal remains were recognized. Identified diatoms include abundant marine planktonic genera,  
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1280 426 such as *Coscinodiscus*, *Asteromphalus*, and *Actinoptychus* (*sensu* Tomas, 1996).  
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1291 427 XRD analysis from available samples of these high-amplitude intervals confirms the log data  
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1293 428 response and shows an increase in terrigenous grains, mainly composed of quartz, calcite, some  
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1295 429 clay minerals, and low amounts of anhydrite, dolomite and magnesite (Fig. 4). Halite appears  
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1298 430 within these samples in a high relative abundance, reaching 45% (Figs 2, 4).  
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1300 431 Due to the nature of well cuttings, samples from these intervals were only retrieved from the  
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1302 432 two thickest beds, at 3367.7 m of the Dolphin well with a thickness of 2.4 m, and the two  
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1304 433 adjacent beds at 3047 and 3034 m with a cumulative thickness of 2.1 m. These intervals are also  
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1306 434 represented by bands of much higher seismic reflectivity than the thin (1.2-1.4 m), overlying  
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1308 435 intervals at 2910 and 2646.5 m. Consequently, the two upper intervals might be the same  
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1310 436 diatomite facies, or only represent marine clastic sediments.  
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#### 1312 437 *4.1.4 Interbedded Evaporites*

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1315 438 This facies is represented in the seismic sections by high-amplitude reflections interbedded  
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1317 439 with nearly transparent intervals with weak internal reflections (Fig. 3), interpreted in previous  
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1319 440 studies to represent an alternation of clastic sediments and evaporites (Gvirtzman et al., 2013a;  
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1321 441 Feng et al., 2016). More recently, Gvirtzman et al. (2017) and Manzi et al. (2018) presented  
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1323 442 further evidence based on well logs from deep-basin wells in the region (Aphrodite), or by  
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1325 443 correlation to more proximal well sections (Hannah-1), showing that this interval mostly consists  
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1327 444 of shale, sand, anhydrite, and halite. The Interbedded Evaporites unit correlates to Unit 5 in  
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1329 445 Gvirtzman et al. (2013). It covers 2560-2025 m in the Dolphin well, and 2548-2276 m in the  
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1331 446 Leviathan-1 well. The GR well log in the Leviathan-1 well indicates 3 to 20 m thick clastic beds,  
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1333 447 interbedded with evaporites varying in thickness from 6 to 30 m. A relatively large diameter  
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1335 448 wellbore used while drilling this interval might have reduced the GR signal and thinner clastic  
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1337 449 beds might not have been detected.  
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1347 450 Due to drilling limitations, the material made available from this interval is partial, and the  
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1349 451 only sampled sequence consists of the lowermost part above 2560 m in the Dolphin well. We  
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1351 452 consider grains from this interval as fallouts from the Interbedded Evaporites unit, confirmed by  
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1353 453 the absence of any indications for a clastic interval in the well-log and seismic data from the top  
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1355 454 of the Main Halite interval, where these grains appear. The samples are made of hard, light to dark  
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1357 455 brown sandy shales (Fig. 3). The grain composition of the >63  $\mu\text{m}$  washed residue is very  
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1359 456 different compared to the underlying Main Halite or Argillaceous Diatomite facies. It contains a  
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1361 457 higher amount of sub-rounded larger sand grains compared to the diatomite facies, different  
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1363 458 types of pyrite including large agglutination of pyritohedrons reaching several mm in size, and a  
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1365 459 diverse faunal composition (Fig. 3). The latter includes few mollusk fragments, ostracods,  
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1367 460 echinoid spines and a relatively rich assemblage of benthic and planktic foraminifera (Fig. 3).  
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1369 461 The most common foraminifera are different *Globigerinoides* species, *Orbulina universa* and  
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1371 462 *Sphaeroidinellopsis seminulina* (younger than 15 Ma; Berggren et al., 2006). Older Cretaceous  
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1373 463 to Eocene foraminifera species are also present, indicating reworking processes, most likely from  
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1375 464 exposed basin margins. These include *Parasubbotina pseudobulloides* (Daninian-Selandian; Fig.  
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1377 465 3.D.13), *Plummerita hantkeninoides* (Maastrichtian; Fig. 3.D.15), and *Subbotina triloculinoides*  
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1379 466 (Paleocene; Fig. 3.D.17). While no overlying samples exist, this interval was logged and a  
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1381 467 reliable lithological interpretation is presented by extrapolating the coupling between sample  
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1383 468 analysis (XRD and micropaleontology) and the log data from the lower to the upper part of the  
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1385 469 section (Fig. 2). The clastic input is estimated from the geophysical data as ~40% of the 535 m  
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1387 470 thick unit in the Dolphin well. However, due to local deformations in the Dolphin well area, the  
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1389 471 Interbedded Evaporites are displaced and their top is reached at the top of the MSC section.  
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1403 472 Comparison with Manzi et al. (2018) suggests that Unit 6 is not represented in the Dolphin  
1404 well but that Unit 5 marks the top of the section (Fig. 5). However, seismic and well-log  
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1406 interpretation indicates that in the Leviathan-1 well another ~200 m of evaporites appear above  
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1408 the Interbedded Evaporites, which corresponds to Unit 6 in Manzi et al. (2018). There, the  
1409 475  
1410 Interbedded Evaporites (Unit 5) are 260 m thinner than in the Dolphin well (Fig. 5). This  
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1412 discrepancy is presumably the result of post-depositional halokinetic deformation and  
1413 477  
1414 imbrication of Unit 5 in the Dolphin well, as imaged in the seismic data (Fig. 5).  
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#### 1418 479 *4.1.5 Argillaceous Evaporites*

1420 480 This interval was not sampled in any of the Levant Basin studies and its interpretation is only  
1421 based on the interpretation of seismic and well-log data. In the Leviathan-1 well this interval  
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1423 covers the uppermost part of the evaporites between 2090 and 2320 m (Fig. 5). The transparent  
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1425 reflective character of this interval in the seismic section includes cyclic darker bands. The unit  
1426 483  
1427 appears to be composed of clastic sediments, probably clays, silts and sands, which are  
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1429 characterized by GR values of 7 to 15 API. Intervals of ca. zero GR are interpreted as  
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1431 argillaceous anhydrite. Gvirtzman et al. (2013; 2017), Feng et al. (2017), and Manzi et al. (2018)  
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1433 refer to this interval as Unit 6, which is generally lumped with the underlying halite as part of the  
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1435 evaporite unit. Regionally, the presence of Unit 6 is limited to the westernmost and deeper areas  
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1437 of the basin, while it is truncated to completely removed landward to the east (Fig. 6). The  
1438 489  
1439 amount of truncation on Unit 6 gradually increases eastwards, eroding also Units 5-2 at the  
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1441 eastern parts (Gvirtzman et al., 2013, Feng et al., 2017; the current study). Both the Dolphin and  
1442 491  
1443 the Leviathan wells are within the deeper areas in which Unit 6 is present, but due to local  
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1445 deformations it might be underrepresented in the Dolphin well. A 5 m clastic and anhydrite bed  
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1447 defines the top of this unit, marked by a nearly transparent seismic interval in the Leviathan-1  
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1459 495 well, as indicated by a sharp drop in GR and drilling penetration rate relative to the overlying  
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1461 496 Pliocene sediments. This anhydrite interval is most likely part of Unit 7 in Gvirtzman et al.  
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1464 497 (2018), or the Nahal Menashe in Madof et al. (2019).  
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#### 1466 498 **4.2 Chronology of halite deposition and well log frequency analysis**

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1468  
1469 499 In order to attain a direct age control on the duration of halite deposition, the halite samples  
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1471 500 were washed and inspected for microfossils, prepared as smear slides, and examined under SEM  
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1473 501 in search for the preservation of eukaryotic life in the evaporites, which failed.  
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1475 502 We also measured the Sr-isotopic composition of evaporite samples in order to compare them  
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1477 503 with the well-established Sr isotope stratigraphy constructed from elsewhere in the  
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1479 504 Mediterranean (e.g., Topper et al., 2011; Roveri et al., 2014; Flecker et al., 2015). This published  
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1481 505 dataset shows that Sr-isotope data from stage 1 lie mainly within error of the ocean-water curve  
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1483 506 (McArthur et al., 2012), suggesting that the Mediterranean was connected to the global ocean  
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1485 507 during the initial phases of the MSC (e.g., Roveri et al., 2014; Flecker et al., 2015). During  
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1487 508 stages 2 and 3 the Mediterranean's Sr record diverges from ocean-water values towards much  
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1489 509 lower ratios that reflect a substantially smaller connection to the global ocean and dominance of  
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1491 510 fresh-water sources such as the Nile, Rhone, and input from the Paratethys, particularly during  
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1493 511 the Lago Mare phase (e.g., Roveri et al., 2014; Flecker et al., 2015). Sr-isotope data from the  
1494  
1495 512 lowest Pliocene are again within error of ocean-water values, indicating an abrupt transition back  
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1497 513 to full connectivity after the MSC (e.g., Roveri et al., 2014; Flecker et al., 2015). Despite the  
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1499 514 wide geographical distribution of the Mediterranean samples from which this published Sr-  
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1501 515 isotope stratigraphy has been constructed, the pattern appears to be consistent, indicating that the  
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1503 516 controlling factor was Mediterranean-Atlantic exchange and that the Mediterranean behaved as a  
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1505 517 single basin throughout the MSC (Flecker et al., 2015). However, the dataset does not include  
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518 samples from these deep-water Eastern Mediterranean sites as they were previously not  
519 available; it therefore makes sense to compare new analyses from these locations with the  
520 existing Sr-chemostratigraphic scheme.

521 Halite is highly soluble and it is therefore challenging to clean samples prior to analysis. We  
522 used the basic method described in Gvirtzman et al. (2017) and Manzi et al. (2018), with  
523 additional eleven different techniques (Fig. S1, Table S1) for attempting to isolate the halite  
524 crystals from any contaminant phases coating the samples such as clay or industrial drilling  
525 additives. The data generated for each of the nine different samples analyzed is highly variable,  
526 ranging from a few values within error of Late Miocene ocean water (McArthur et al., 2012), to  
527 substantially higher values (Fig. S1, Table S1). There is no consistency between the data  
528 generated and the technique used for dissolving the halite (Fig. S1, Table S1), suggesting that we  
529 have not been able to reliably isolate the halite from contaminant phases coating the crystals by  
530 any of the methods used. We therefore conclude that none of this data should be considered as  
531 representing a primary record of Eastern Mediterranean water at this time.

532 Similar high values have been reported for halite from other industrial wells in the Levant  
533 Basin (Gvirtzman et al., 2017; Manzi et al., 2018). Manzi et al. (2018) attributed the  
534 anomalously high values to “local, diverse, short-term Sr input”, but did not specify what this  
535 input might be. One possibility is that these published halite values from industrial cuttings may,  
536 like our data, be contaminated. We conclude that a robust Sr-isotope record for the deep-basin  
537 halite deposits will only be achieved either by establishing a reliable method for removing  
538 contaminant phases or by recovering halite samples without the use of industrial drilling fluids,  
539 e.g., through scientific drilling (Camerlenghi et al., 2014).

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1571 540 Next, we attempted to construct a chronostratigraphic framework for the Levant MSC  
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1573 541 deposits based on astrochronological tuning. We carried out spectral analysis of GR and RE  
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1575 542 well-logs to correlate the Levant MSC section to astronomical target curves, and the more  
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1577 543 proximal to onshore Mediterranean MSC deposits. REDFIT spectral analyses (Schulz and  
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1579 544 Mudelsee, 2002) of the Dolphin and Leviathan-1 well-log data from the base to the top of the  
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1581 545 evaporite unit (3616-2025 m in the Dolphin well, divided into three intervals for spectral  
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1583 546 analysis; Fig. S2) indicates statistically significant, periodical signals in the RE and GR logs.  
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1585 547 However, the GR produces a weaker signal than the RE log within the massive halite intervals.  
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1587 548 This is expected, as pure halite does not contain the elements U, Th, and K and their decay series  
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1589 549 responsible for natural GR radiation emitted by rocks. However, several examples indicate how  
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1591 550 different log responses occur within halite sequences. For example, inner-halite variations such  
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1593 551 as thin clay laminae caused by microstratification within the brines might occur (Sonnenfeld,  
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1595 552 1983). Alternatively, thin sulphate layers (Biehl et al., 2014) have also been shown to produce  
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1597 553 log-responses.

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1601 554 Each of the analyzed log segments is characterized by several frequency peaks exceeding the  
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1603 555 chi 95% confidence interval (Fig. S2). Each segment was bandpass filtered according to these  
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1605 556 frequencies, and the fit of the filtered version to the original well-log was examined, ultimately  
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1607 557 selecting the best-fit result for subsequent analysis. Both logs are composed of significant and  
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1609 558 approximately overlapping periodical frequencies, with an average cycle thickness of ~50 m  
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1611 559 (Fig. S2). While the RE log appears to be more attuned to inner-halite variations in the Main  
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1613 560 Halite interval, the GR log is more consistent and provides a more reliable fit to the well log  
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1615 561 target curve in the units above 2833 m. Consequently, the Dolphin well cyclostratigraphy is  
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1617 562 constructed from information derived from the GR and RE logs that cover the lower and upper  
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1627 563 parts of the section (Fig. S2). The lower part of the Main Halite interval (cycles 1-11; Fig. S2) is  
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1629 564 not very well represented by the Gaussian filter, with some five cycles that fit well with the  
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1631 565 target curve. The upper part of the Main Halite interval is best filtered by using the RE log with a  
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1633 bandwidth of 49 m (cycles 12-24; Fig. S2). The cycles within the upper part of the section in the  
1634 566 Interbedded Evaporite interval are picked up relatively clearly by the GR log (cycles 25-32; Fig.  
1635  
1636 567 S2). However, as the Dolphin well section from the Interbedded Evaporites and above  
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1638 568 experienced significant deformation (Figs 5, 6), the well-log cyclostratigraphy of the upper part  
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1640 569 of the studied section is not reliable in this well.  
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1644 571 Several frequency peaks exceeding the chi 95% confidence interval were also identified in  
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1646 572 the Leviathan-1 well-log analysis, where deformation is reduced and Unit 6 is represented (Figs  
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1648 573 5, 6). The RE log was cleaned from outlier spikes and used for bandpass filtering. The original  
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1650 574 log includes several short intervals in which values range from 10's or 100's of ohm\*m to  
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1652 575 extremely high 18,000+ ohm\*m values, masking cyclic trends in the data. Figure 5 shows the  
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1654 576 cleaned RE log overlain on the seismic data. There is a much-improved fit between the log and  
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1656 577 filtered cycles, relative to the Dolphin well, with only a few examples of a misfit between the  
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1658 578 two. A good fit is also generally apparent between the seismic signal and the well-log response.  
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1660 579 The Main Halite interval includes 19 cycles, in which cycles 4 and 5 are within the first  
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1662 580 Argillaceous Diatomite beds, and cycles 11-13 are within the second. The cycles within the  
1663  
1664 581 Interbedded Evaporite interval are picked up relatively clearly by the RE log (cycles 19-27; Fig.  
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1666 582 5). In the Argillaceous Evaporites in the uppermost part of the studied section in the Leviathan-1  
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1668 583 well, the RE log response fits with banding in the seismic data, which is also picked by bandpass  
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1670 584 filtering (cycles 27-33; Fig. 5).  
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1684 585       Consequently, bandpass filtering of the well logs results in ~33 cycles from the base to the top  
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1686 586       of the evaporite sequence in the Levant Basin. In the next two sections, we present different  
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1688 587       findings supporting the occurrence of lithological cycles along the studied section, followed by  
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1690 588       the astrochronologic interpretation of these cycles in the discussion section.

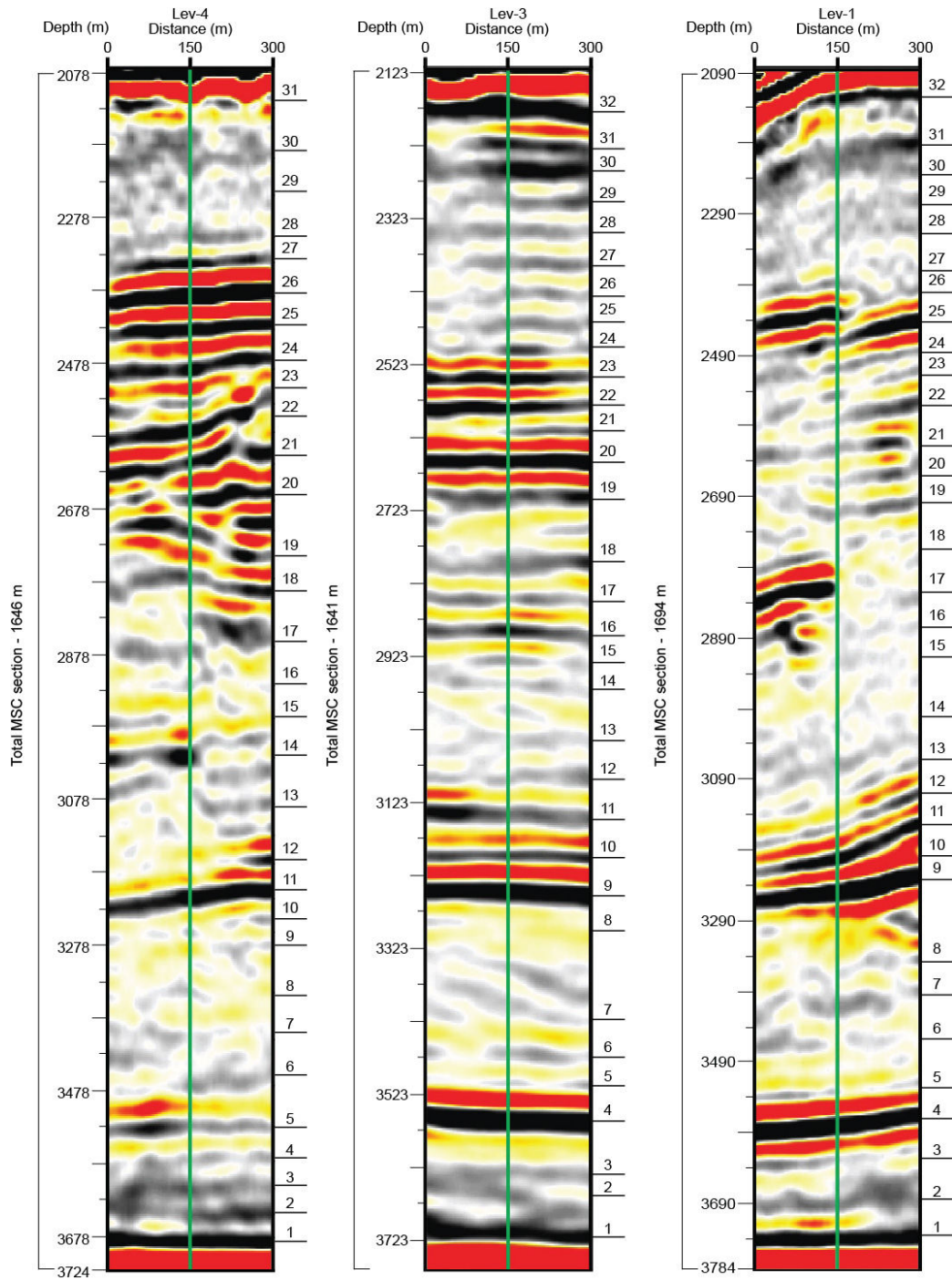
### 1692 589       **4.3 Cyclicity of seismic reflective phases**

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1695 590       Modern high-quality 3D seismic imagery represents a new frontier for astronomical  
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1697 591       calibration, potentially adding a chronological time-frame for seismic stratigraphy. However, in  
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1699 592       most marine settings, precession-scaled cycles are registered at a thicknesses-to-cycles ratio  
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1701 593       which has a much higher resolution than the seismic data. Yet, several studies show a good  
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1703 594       match between the number of precession-induced astronomic cycles and the number of positive  
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1705 595       vs. negative seismic phases within MSC deposits (Driussi et al., 2015; Geletti et al., 2014). This  
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1707 596       is explained by the considerably higher sedimentation rates that characterize evaporite deposits,  
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1709 597       relative to the much lower rates typical of normal-marine clastic or carbonate deposition. The  
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1711 598       higher sedimentation rates result in an improved alignment between the spacing, or resolution, of  
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1713 599       lithologic variations and the resolution of the seismic imagery. As orbital forcing was repeatedly  
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1715 600       identified as determining lithological variations during the MSC (e.g., Krijgsman et al., 1999;  
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1717 601       Ochoa et al., 2015; Roveri et al., 2014a; Sierrro et al., 2001; van den Berg et al., 2015), seismic  
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1719 602       data recording these variations can be used with caution for strengthening the well-log  
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1721 603       astronomical tuning-based age models. This is not the case for the Pre-Evaporites in this area,  
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1723 604       which deposited at an average sedimentation rate of 11.4 cm/kyr and a cycle thickness of around  
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1725 605       2-3 m, as shown by Meilijson et al. (2018). This thickness is below the resolution of the seismic  
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1727 606       data. Here, we use the seismic 3D data for additional validation of our results from well-log  
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607 curves based on REDFIT spectral analysis and bandpass-filtering within the Main Halite and  
608 overlying intervals.

609 In practice, the seismic tuning analysis was performed by counting the number of reflectivity  
610 phases on three different sections where wells were drilled within the 3D geophysical dataset of  
611 the study area (Figs 1, 7). Yet, as halokinetic deformation affected the Levant deep-basin  
612 evaporites, and particularly their upper units (Gvirtzman et al., 2013a), spatial variations are  
613 expected even considering a scenario of regionally uniform deposition. Such variations in the  
614 number and thickness of cycles are indeed observed when comparing different seismic sections,  
615 reflecting the local variabilities (Fig. 7). In total, a consistent number of ~30 reflectivity cycles is  
616 identified in different locations, which is in agreement with the cyclicity identified through well-  
617 log spectral analysis.



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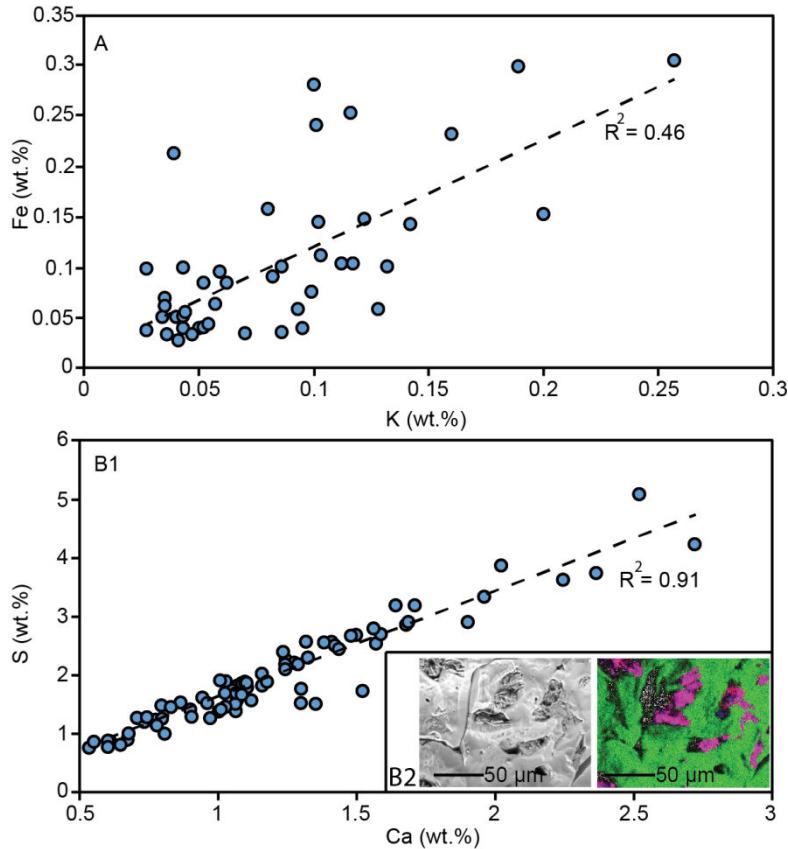
619 *Figure 7. Seismo-cyclostratigraphy of three seismic profiles around wells in the study area.*

620 Three depth-migrated profiles that are aligned with wells in the central Levant. Black lines  
 621 with numbers on the right hand side of each seismic profile represents a reflectivity phase (black)  
 622 cycle count along the section. Left bar show actual depth for each section and the total depth  
 623 from base to top of the MSC section in each well.

#### 4.4 Elemental variations within evaporite samples

The wellbore cuttings do not allow recognition of macro-scale sedimentological features, which may reflect the cyclicity identified in the well logs and seismic data within the halite sequence. Tuning of marginal MSC sections has been done based on lithological transitions, such as branching selenite to massive selenite, or chaotic deposits to clastic evaporites in stages 1-3 (e.g., Roveri et al., 2014a), or diatomite-shale-carbonate transitions in the Pre-Evaporites (Ochoa et al., 2015; Sierro et al., 2001). Here, we explore whether minor inner-halite chemical variability down-section can account for the filtered cycles and variable log response within apparently massive and homogenous halite. Other Miocene intervals of homogeneous lithology have also been shown to contain cyclic changes in the chemical composition of the sediments (van den Berg et al., 2015), which are assumed to represent shifts in the depositional environment. We hypothesize that these variations, if present in deep Mediterranean basins, could correspond to: 1) variations in riverine runoff and associated influx of clastic material into the basin, and/or 2) shifts in the degree of evaporation determining the type of deposited evaporites. Both of these drivers can be related to orbital forcing (Marzocchi et al., 2015; Simon et al., 2017).

We observe a relatively low correlation ( $R^2=0.46$ ; Fig. 8A) between Fe and K in the Levant halite samples, which is not in agreement with the occurrence of continentally-derived material transported to the Eastern Mediterranean. In contrast, a high elemental correlation ( $R^2=0.91$ ; Fig. 8B1) is observed between S and Ca, which confirms that low and variable amounts of minerals rich in  $\text{CaSO}_4$  (i.e., gypsum and anhydrite) represent an integral part of evaporite deposition in the Main Halite of the deep Levant Basin.



646  
647 *Figure 8. X-ray fluorescence elemental analysis of the Levant evaporites*

648 Results of XRF elemental analysis are shown for 77 halite samples for specific elemental  
649 composition. (A) Note the low correlation between iron and potassium, while (B1) shows a high  
650 sulfur to calcium correlation. The high correlation between sulfur and calcium is corroborated by  
651 SEM-EDS imagery and element maps (halite sample from 3058 m; (B2)) showing the  
652 distribution of Na (green), Ca (blue) and S (red), indicating the occurrence of gypsum  
653 microcrystals (purple; B2) within cavities of the larger and much more common halite crystals.

654  
655 This notion is further confirmed by the recognition of calcium sulfate microcrystals minerals  
656 within the halite cuttings (Fig. 8B-2). Note that not all halite crystals include a similar  
657 precipitation of calcium sulfates in small pores. We suggest that shifts in the amount of gypsum  
658 or anhydrite deposition along the section might correspond with the cycles obtained by well-log  
659 spectral analysis.

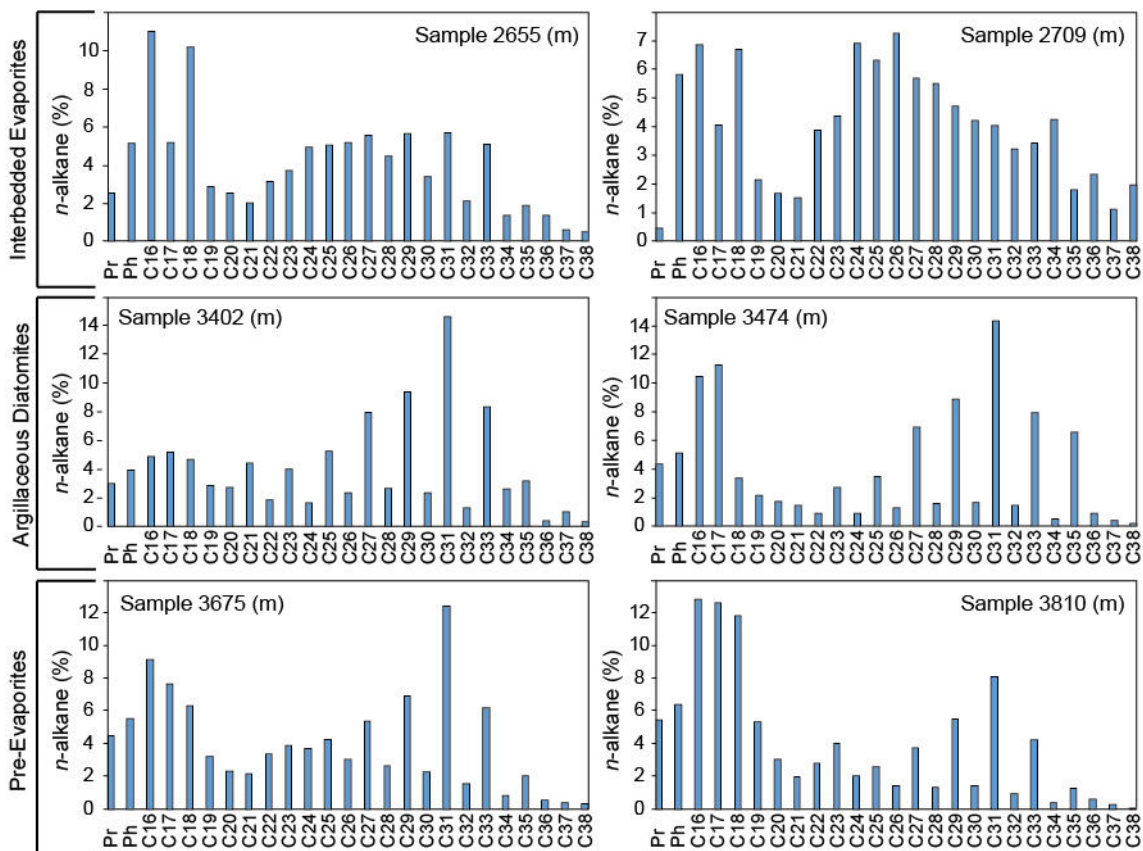
#### 4.5 Organic geochemistry as a stratigraphic marker

Biomarker data allow us to identify sources of sedimentary organic matter preserved in the cuttings as well as to gain insights into its thermal history. We observed distinct differences in the biomarker distribution found in the Pre-Evaporites, the Argillaceous Diatomites within the Main Halite deposits, and the overlying Interbedded Evaporites interval. The *n*-alkanes range from *n*-C<sub>16</sub> to *n*-C<sub>38</sub> (Table 1, Fig. 9), and their distribution varies between samples. For example, while short- and long-chain alkanes are more predominant in the Pre-Evaporites and the Argillaceous Diatomites, mid-chain alkanes are more prominent in the Interbedded Evaporites. Additionally, the carbon preference index (CPI) of long-chain *n*-alkanes, which portrays the degree of oddity in the distribution of the different *n*-alkanes, varies around 5-7 in the Pre-Evaporites, 4-12.3 in the Main Halite (Argillaceous Diatomites) interval, and around 1.9-2.9 in the Interbedded Evaporites (Table 1; Fig. 10). The Argillaceous Diatomites also contain the lowest Pr/Ph ratios (Table 1, Fig. 10) compared to other samples. The relative abundance of long-chain *n*-alkanes (C<sub>25</sub>–C<sub>35</sub>) is more elevated within the Argillaceous Diatomites and Pre-Evaporite. This is reflected in the ratio of long chain (C<sub>25</sub>-C<sub>37</sub>) to short chain (C<sub>16</sub>-C<sub>21</sub>) *n*-alkanes, which maximize in the Argillaceous Diatomites (1.9), followed by the Interbedded Evaporites (1.6) and the Pre-Evaporites (1.2). The C<sub>31</sub> *n*-alkane commonly is the most dominant homologue.

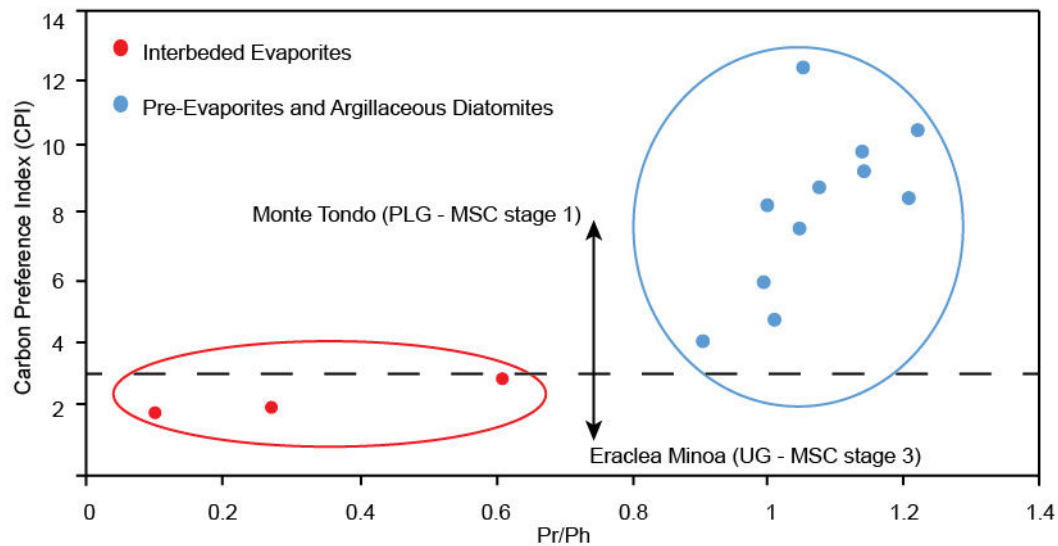
Selected hopane- and sterane-based thermal maturity indices (Table 2; Fig. 11; Peters and Moldowan, 1993; Rullkötter and Marzi, 1988; Peters et al., 2005) also indicate major differences between samples from the Pre-Evaporites and Argillaceous Diatomites, relative to those from the lower part of the Interbedded Evaporites. As summarized in Table 2, the diatomite facies exhibit the lowest thermal maturity values, to be followed by the Pre-Evaporites, while much more mature indices are reached in the overlying Interbedded Evaporites. This is clearly indicated by

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683 the presence of hopanes with the biological  $\beta\beta$  configuration, in addition to low values of the  $C_{31}$   
684 S/R hopanes ratio and the  $C_{28}$   $\alpha\alpha\alpha$  20S/20R steranes ratio, and more elevated values of the  $C_{30}$   
685  $\beta\alpha/\alpha\beta$  hopanes ratio in immature samples (Fig. 11). Additionally, the Argillaceous Diatomites  
686 samples exhibit a lack of re-arranged steranes compared to the overlying and underlying  
687 intervals (Fig. 11; Table 2).



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689 *Figure 9. n-alkane distribution in non-halite intervals.*  
690 Two samples from each depositional unit (left and right columns) show the relative abundance of  
691 pristane (Pr), phytane (Ph), and  $C_{16}$ - $C_{38}$   $n$ -alkanes. Note the odd-over-even carbon-number  
692 predominance of long-chain  $n$ -alkanes in the Argillaceous Diatomites (center) and Pre-  
693 Evaporites (lower) relative to the overlying Interbedded Evaporites. Also observe the higher CPI,  
694 i.e., the distribution of  $n$ -alkanes, in the Pre-Evaporites and Argillaceous Diatomites relative to  
695 the Interbedded Evaporites, and higher relative abundance of medium-long chained compounds.

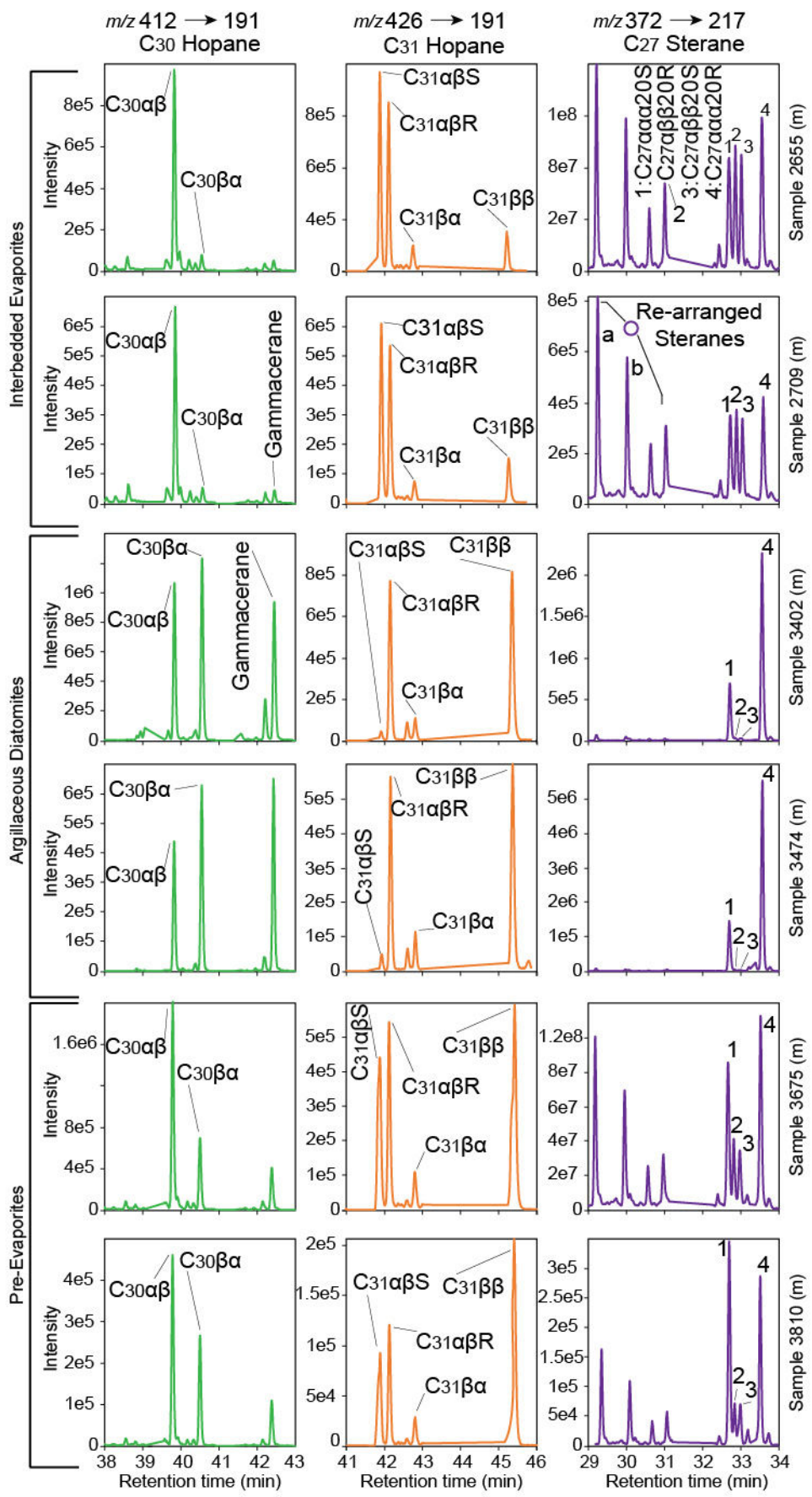


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698 *Figure 10. Pristane/phytane ratio to carbon preference index (CPI) plot.*

699 Legend indicates the strata of plotted samples. Horizontal dashed line indicates the separation  
700 of CPI values of marginal section across the MSC reported by Vasiliev et al. (2017). Note that  
701 the samples from the Interbedded Evaporites plot in the area of values measured in stage 3 of the  
702 MSC (Vasiliev et al., 2017), while the lower samples from the Levant plot in the area of MSC  
703 stage 1. Also note the separation in Pr/Ph values between the Interbedded Evaporites relative to  
704 the Pre-Evaporites and Argillaceous Diatomites.



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706 *Figure 11. Distribution of selected bacterial hopanes and algal steranes.*

707 Two samples from each depositional unit (left and right columns) were investigated for the  
708 distribution of aliphatic hydrocarbons using selective reaction monitoring (SRM) analysis. Each  
709 sample (numbered on the right) includes a chromatogram for three given SRM transitions: 412  
710 → 191 (C<sub>30</sub> Hopane); 426 → 191 (C<sub>31</sub> Hopane); 372 → 217 (C<sub>27</sub> Sterane). The C<sub>27</sub> rearranged  
711 steranes are marked as (a) C<sub>27</sub>β $\alpha$  20S and (b) C<sub>27</sub>β $\alpha$  20R. High ratios of C<sub>31</sub>αβS/R hopanes and  
712 C<sub>27</sub>αααS/R steranes, along with low values of C<sub>31</sub>ββ/αβ and C<sub>30</sub>ββ/αβ hopane ratios, indicate a  
713 higher, yet mixed, maturity of the organic matter preserved in the Interbedded Evaporite shale  
714 samples compared to samples from the Pre-Evaporites and Argillaceous Diatomites. The  
715 underlying diatomite facies sediments are immature in nature, while the Pre-Evaporite shale  
716 samples exhibit mixed signatures (e.g., high C<sub>31</sub>ββ/αβ hopanes and C<sub>27</sub> αααS/R steranes).

## 5. Discussion

### 5.1 Deep-sea halite depositional environment

The halite in the Dolphin well appears to be a pure, homogeneous layer, indicating a monotonous deposition of halite in the deep Levant Basin. Transmitted-light microscopy and SEM analysis of halite crystals (<0.5 cm) throughout the section reveals no distinct sedimentological variations. XRD analysis also confirms a uniform, halite-dominated mineralogical composition (Fig. 4). Gypsum microcrystal were observed within several halite crystals as seen in SEM-EDS (Fig. 8B-2), and elemental variations supporting shifts in the relative amounts of calcium sulfates deposited along the halite part of the section were apparent in XRF analysis (Fig. 8). However, we found no features similar to the lithological variations reported from the Realmonte salt mine (Lugli et al., 1999) or the intermediate depth halite of the Balearic Basin (Site 134; Lugli et al., 2015), such as cumulates of halite plates settled out from a stratified water column, plate cumulates in a shallowing-upward sequence containing kainite layers, or cumulates of skeletal hoppers with chevron overgrowths. The above conclusion might be biased due to the usage of well cutting, possibly not allowing to recognize these features. However, the mm-scale variations in the salt deposits shown by Lugli et al. (2015) should have been recognizable in the halite well cuttings. The lack of comparative features between the marginal halite and the Levant deep-basin halite is also evident when comparing the halite samples in the Dolphin well and halite deposits penetrated by DSDP drilling. There is a clear distinction between the featureless Dolphin halite and the halite interbedded with detrital sand and small anhydrite nodules recovered at DSDP Site 134 offshore Sardinia in the margins of the western Mediterranean (Hsü et al., 1973). The halite sampled in Site 134 is banded similarly to the Sicily halite reported by Lugli et al. (1999), with alternative cloudy and translucent beds.

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740 Similarly, the banded halite and polyhalite at DSDP Sites 374, 375 and 376 in the Eastern  
741 Mediterranean (Garrison et al., 1978) does not resemble the homogenous halite recovered in the  
742 Dolphin well. The homogeneous nature of the halite observed in the Dolphin well suggests  
743 continuous deep-sea deposition, in comparison to halite deposition in the shallower marginal  
744 basins.

745 Modern analogs for ancient deep-water halite depositional environments are scarce. An  
746 exception is the hypersaline Dead Sea, in which active precipitation of halite occurs within the  
747 deepest parts of the basin (Arnon et al., 2016; Sirota et al., 2016, 2017; Steinhorn, 1983; Stiller et  
748 al., 1997). The Dead Sea floor is divided into two principal environments: a deep, hypolimnetic  
749 lake floor, and a shallow, epilimnetic lake floor (Sirota et al., 2016, 2017). Halite continuously  
750 precipitates with seasonal variations influencing the type of halite formation on the deeper  
751 hypolimnetic lake floor. However, the shallow epilimnetic lake floor is also subject to seasonal  
752 variations, which produce annual unconformities related to halite deposition and dissolution. The  
753 epilimnion part of the lake is undersaturated during the summer and halite is dissolved, while  
754 winter is characterized by a heavily supersaturated water column and halite is crystallized (Sirota  
755 et al., 2016). Summer is associated with higher loss of water by evaporation from the lake  
756 compared to the winter. Sirota et al. (2016) argue that the seasonal halite deposition cycle in the  
757 Dead Sea epilimnion is controlled by the decrease in the saturation with increasing temperature,  
758 which overcomes the effect of enhanced summer evaporation. The hypolimnion is supersaturated  
759 and halite is crystallized throughout the year, with higher supersaturation and higher  
760 crystallization rates during winter. During summer, the undersaturated epilimnion dissolves  
761 halite, forming highly saturated dense solutions. These solutions flow to the hypolimnion, which  
762 becomes supersaturated and crystallizes halite. This process results in focusing of halite deposits

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763 in the deep hypolimnetic parts of the evaporitic sea, and thinning of the shallow epilimnetic  
764 deposits occurs (Sirota et al., 2016, 2017). The Dead Sea modern analogue provides a  
765 mechanism for explaining the great thickness of the deep Mediterranean MSC halite deposit. A  
766 similar model might have applied during the MSC, with halite dissolution in the marginal and  
767 intermediate basin evaporites, and focusing and thickening of halite deposition in the deeper  
768 parts of the basin, as also partly proposed by Roveri et al. (2014c).

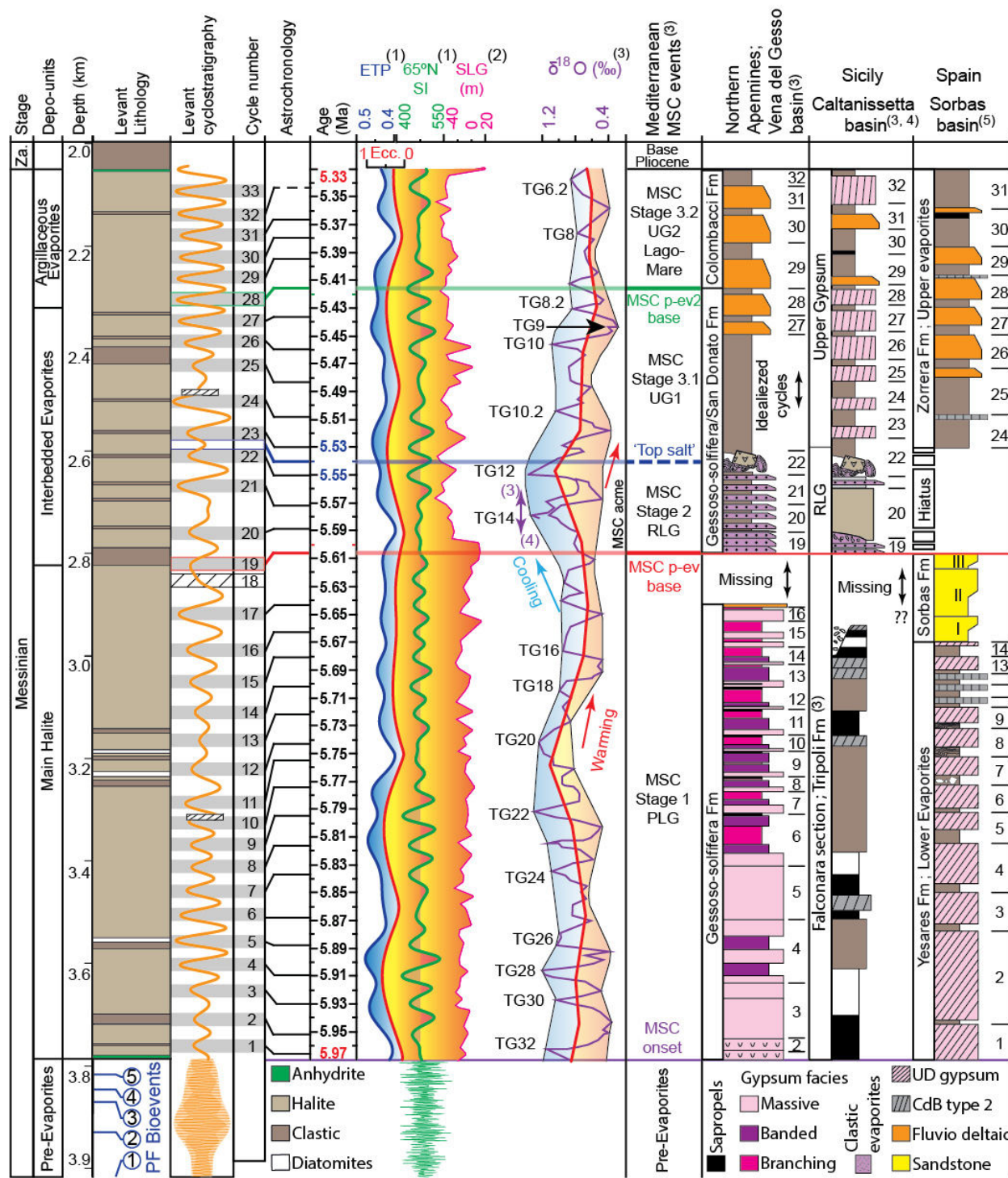
## 769 **5.2 Stratigraphic markers in deep basin MSC deposits**

### 770 *5.2.1 Deep-basin diatomites as environmental and lithostratigraphic markers*

771 As no chronostratigraphic indicators were found in the studied section, we aim to use the  
772 litho-chemical analysis performed on the Dolphin well samples to identify lithostratigraphic and  
773 chemostratigraphic markers that may serve as tie-points for establishing an age model for the  
774 deep basin MSC deposits (Fig. 12). In this context, the occurrence of diatomites within the Main  
775 Halite unit provides a primary observation. Diatomites are known to occur within Pre-Evaporite  
776 and PLG intervals in some of the marginal sections (Dela Pierre et al., 2014; Hilgen et al., 2007;  
777 Hilgen and Krijgsman, 1999; Krijgsman et al., 2001; Manzi et al., 2011; Roveri et al., 2014a),  
778 and more rarely within stage 3 Upper Gypsum deposits (e.g., Eraclea Monia section; Manzi et  
779 al., 2009). Diatom-rich aggregates within laminated layers, appearing as mudstone intervals  
780 interbedded within the PLG deposits of the Piedmont basin, were used by Dela Pierre et al.  
781 (2014) to establish the existence of normal-marine (not brackish or hypersaline) waters during  
782 deposition of non-evaporitic intervals during stage 1 of the MSC. Here we show that open-  
783 marine planktonic diatom taxa abundant in the Piedmont during the PLG (e.g., *Coscinodiscus* sp.  
784 and *Thalassionema longissimi*) are also abundant or closely related to abundant species within  
785 the Dolphin assemblage.

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788 *Figure 12. Astronomical age model and regional correlation of the Levant MSC*  
 789 *The Levant interpreted lithology (left, from Fig. 2), biostratigraphic reference levels (PF –*  
 790 *planktic foraminifera, below) and filtered well-log model (Fig. 5) determine a cyclostratigraphic*

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791 *model, resulting with 33 cycles for the Levant MSC (shaded cycles). Note the significantly lower*  
792 *cycle frequency in the Pre-Evaporites (2.3 m compared to 51 m per-cycle), due to the much*  
793 *higher sedimentation rates in the evaporites interval. This cyclostratigraphic model is tuned to*  
794 *astronomic target curves (center) of ETP (blue; calculated as eccentricity (Ecc; red) + obliquity*  
795 *- precession ((1) Laskar et al., 2004), 65°N summer insolation (65°N SI; green) (Laskar et al.,*  
796 *2004), and marginal MSC deposits (right columns) based on astronomical calibrated ages and*  
797 *cycles identified across the Mediterranean ((1) Laskar et al., 2004; (3) Roveri et al., 2014a,*  
798 *CIESM (2008); (4) Manzi et al., 2011; (5) Krijgsman et al., 2001). The drop in sea level (SLG;*  
799 *sea level Gibraltar; (2) Ohneiser et al. 2015) corresponding to glacial peaks TG12-14 ( $\delta^{18}O$ ; as*  
800 *summarized in Roveri et al. (2014)) marks the top of the Main Halite unit. The shift to post-*  
801 *evaporitic and clastic deposits of MSC stage 3 (Hilgen et al., 2007; Krijgsman et al., 2001;*  
802 *Laskar et al., 2004; Roveri et al., 2014), through a stepwise deglaciation associated with sea-*  
803 *level rise (TG12-9), is here astronomically tuned to enhanced clastic deposition in the*  
804 *Interbedded Evaporites and Argillaceous Evaporites units of the Levant.*

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806 To date, there are no reports of diatomites, or a diatom-rich assemblage in stage 2 of the MSC  
807 across the Mediterranean. Based on the taxonomic similarities between the deep and marginal  
808 planktonic marine diatom assemblages, we propose that the Levant diatomites constitute a  
809 temporal lithostratigraphic marker. If we follow the interpretation for the occurrence of planktic  
810 marine diatoms as indicators of partial connectivity with the Atlantic Ocean (Dela Pierre et al.,  
811 2014; Hüsing et al., 2009; Krijgsman et al., 2000), then their appearance interbedded within the  
812 halite in the Levant suggests that deposition of the halite layer occurred at a time of at least  
813 partial, periodic Atlantic connectivity, most likely during deposition of the PLG on the margins  
814 (5.97-5.6 Ma).

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2523 815 *5.2.2 Allochthonous grains in the Interbedded Evaporites-Argillaceous Evaporites and stages 2-*  
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2528 817 The abrupt change that marks the onset of enhanced clastic input in the Interbedded  
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2530 818 Evaporites in the Levant Basin, together with endemic and reworked Eocene and Cretaceous  
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2532 819 foraminifera into the basin, matches other similar episodes reported from the MSC in the  
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2534 820 Mediterranean. Primarily, these are the clastic-rich deposits that result in the deposition of the  
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2536 821 Reworked Lower Gypsum (stage 2) and the Upper Gypsum and Lago-Mare deposits (stage 3) on  
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2538 822 the margins. These clastic deposits, including a similar abundance of minerals and reworked  
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2540 823 fauna, are not only reported from marginal sections (e.g., Lofi et al., 2011; Roveri et al., 2014),  
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2542 824 but also from cores of deeper parts of the basin (e.g., Site 124 in the Western Med (Ryan et al.,  
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2544 2007), Site 654 in the Tyrrhenian Sea (Borsetti et al., 1990), and from Sites 374 and 376 in the  
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2546 825 Eastern Mediterranean (Cita et al., 2006; Hsü et al., 1978a, 1978b)).  
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2549 827 DSDP Sites 375 and 376 at the Florence Rise in the Eastern Mediterranean recovered  
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2551 828 nannofossil marlstones and dolomitic marlstones of latest Miocene age, overlying a gypsum with  
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2553 829 marlstone sequence (Hsü, et al., 1978b). The gypsum with marlstone, which are interpreted as  
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2555 830 deposits of a shallow subaqueous environment, are followed downwards by anhydrite and halite  
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2557 831 at Site 376 and are collectively recognized as the upper part of the Mediterranean evaporites. The  
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2559 832 interbedded gypsum contains reworked Cretaceous, Paleogene and lower/middle Miocene  
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2561 833 foraminifera and nannofossils, similar to the fauna identified in the clastic interval of the  
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2563 834 Interbedded Evaporites in the Dolphin well. The reworked fauna from Florence Rise are  
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2565 835 common to abundant in the bedded evaporites and rare to absent in the overlying Pliocene and  
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2567 836 underlying Tortonian and Serravallian (Hsü, et al., 1978b), indicating a distinctive phase of  
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2569 837 reworked sediments deposited within the Mediterranean basins. The sedimentary response of the  
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2579 838 Interbedded Evaporites and Argillaceous Evaporites (Units 5 and 6, respectively; Gvirtzman et  
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2581 al., 2013; 2017; Manzi et al., 20018) in the Levant Dolphin and Leviathan-1 wells (from ~2270  
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2583 m in the Dolphin well, Figs 5, 12) resembles similar observations reported from shallower  
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2585 deposits in the Levant. For example, the Afiq Formation overlies the anhydrite-siliciclastic stage  
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2587 2-RLG equivalent Mavqiim Formation (Druckman et al., 1995; Lugli et al., 2013) and was  
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2589 penetrated by the Or-South 1 well. It consists of Eocene-aged lithoclasts made of limestone,  
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2591 dolomite, and chert- and quartz-rich sand, overlying a conglomerate unit with brackish ostracods  
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2593 indicating a plausible correlation to the Lago-Mare stage (Derin, 2000). A fluvial or sabkha  
2594 845  
2595 environment is attributed to this interval with subaerial exposure, supporting the idea of a  
2596 846  
2597 considerable desiccation phase and subaerial exposure near the end of the MSC (Cita et al.,  
2598 847  
2599 1978; Lofi et al., 2011; Madof et al., 2019; Ryan, 1978). Similar lithologies, including clasts of  
2600 848  
2601 Eocene and Cretaceous age, were described from the marginal Nir-1 well in the Levant Basin  
2602 849  
2603 above an erosion surface and beneath earliest Pliocene marls (Frey-Martinez et al., 2007).  
2604 850  
2605 Similar clastic-conglomeratic and sandy lithologies are also reported from the Messinian  
2606 851  
2607 Qawasim and Rosetta formations offshore Egypt (Leila et al., 2016); the latter correlates with the  
2608 852  
2609 Afiq Formation in the Levant (Derin, 2000). Unfortunately, no samples are available from above  
2610 853  
2611 the base of the Interbedded Evaporites in the deep Levant Basin to further confirm the  
2612 854  
2613 lithological correlation between these sections and the deep Levant Basin. Correlation to more  
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2615 proximal sections and well-log interpretations indicate that the overlying Argillaceous Evaporites  
2616 856  
2617 mark a shift to more clastic and gypsum/anhydrite deposition (see also Gvirtzman et al., 2013;  
2618 857  
2619 2017; Manzi et al., 2018).  
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2624 859 We argue that the main change in the halite unit, characterized by mixing of clastic material  
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2626 860 into the deep-basin deposits at the base of the Interbedded Evaporites correlates with the  
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861 beginning of major sea-level drawdown and introduction of clastic material into the entire  
862 Mediterranean Basin, from stage 2 of the MSC (5.6 Ma) through the Upper Gypsum and Lago  
863 Mare stages in the marginal basins (5.55-5.33 Ma; Argillaceous Evaporites in Fig. 12). During  
864 stage 2, sea-level drawdown eroded and redeposited the PLG gypsum into the marginal and  
865 intermediate parts of the basin (e.g., Lofi et al., 2011). The deep-basin expression of this  
866 regression might be the fine-grained clastics, including older reworked fauna, reaching the  
867 Mediterranean depocenters. However, to further test this idea and try to distinguish between  
868 stage 2 and 3 sediments, we compare biomarker distribution across the basin, and identify  
869 sedimentary cycles within the MSC of the Levant Basin.

### 870 *5.2.3 Basin-wide transport of organic matter*

871 The *n*-alkane distribution and CPI values of the Levant samples (Figs 7 and 8; Table 1) are  
872 similar to some extent to those obtained from marginal and onshore MSC successions (Vasiliev  
873 et al., 2017), and provide further support for the introduction of reworked and mixed material  
874 into the Levant during the deposition of the Interbedded Evaporites. The *n*-alkane distribution of  
875 Mediterranean MSC samples covering the entire 640-kyr-long MSC interval shows distinct  
876 dissimilarities between several marginal to intermediate-depth sections (Vasiliev et al., 2017):  
877 The Monte Tondo (Primary Lower Gypsum; MSC stage 1), Realmonte salt mine (Halite and Re-  
878 sedimented Lower Gypsum; MSC stage 2), and Eraclea Minoa (Upper Gypsum/Lago Mare;  
879 MSC stage 3). The Delphine well *n*-alkane distribution shows a higher abundance of short-chain  
880 homologues in the Levant relative to marginal sections (Vasiliev et al., 2017), likely due to the  
881 lower relative input of terrestrial organic matter in more distal depositional settings. Several  
882 similarities exist between both data sets. Vasiliev et al. (2017) reported CPI values of 3.0-7.9 at  
883 Monte Tondo (stage 1), and 1.7-3.7 at Eraclea Minoa (stage 3; Fig. 10). While CPI values were

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2691 884 not reported from the halite samples of the Realmonte salt mine, Vasiliev et al. (2017) show two  
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2693 885 different types of organic matter: 1) autochthonous sediment associated with gypsum or halite  
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2695 886 deposited in place, and 2) allochthonous material associated with clastic sediments and transport.  
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2698 887 Marked similarities in CPI values are therefore noted between the Levant and marginal locations  
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2700 888 described by Vasiliev et al. (2017), with CPI values of 4.0-12.3 in the Main Halite interval  
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2702 889 (indicating stage 1), and 1.9-2.9 in the Interbedded Evaporites interval (indicating stages 2-3)  
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2704 890 (Fig. 10).

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2706 891 Vasiliev et al. (2017) also suggest that dissimilarities in the biomarker and isotopic  
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2708 892 composition of stages 1 and 2, relative to stage 3 sediments, may be attributed to the outflow of  
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2710 893 Black Sea (i.e., Paratethys) waters and their mixing into the Mediterranean, which paved the way  
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2712 894 for Paratethyan ‘Lago-Mare’ type fauna. For instance, the distribution of *n*-alkanes and CPI  
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2714 895 values in stage 3 at Eraclea Minoa are more evenly distributed and lower relative to those of  
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2716 896 stage 1 (fig. 3 in Vasiliev et al., 2017). We report a similar distinction in the *n*-alkane distribution  
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2718 897 between the upper clastic samples and underlying sediments (Table 1, Fig. 9). A much stronger  
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2720 898 odd-over-even predominance (i.e., higher CPI values) is observed in the Argillaceous  
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2722 899 Diatomites, together with more elevated long-chain over short-chain *n*-alkanes values  
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2724 900 (LCA/SCA; Table 1) and maturity parameters (Fig. 11; Table 2). This indicates more immature  
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2726 901 source rocks with significantly different sources of the organic matter in the Main Halite relative  
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2728 902 to the Interbedded Evaporites sediments (Bray and Evans, 1961; Scalan and Smith, 1970).

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2730  
2731 903 The distribution of stereoisomers of algal steranes and bacterial hopanes (Fig. 11; Table 2)  
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2733 904 reflects the transformation, or stereoisomerization from biological epimers to a more stable  
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2735 905 geological molecular configuration as a consequence of thermal alteration (Peters, 1986; Peters  
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2737 906 et al., 2005, 1980). The evidence for enhanced thermal maturity in the Interbedded Evaporites  
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2747 907 relative to the underlying deposits (Fig. 11; Table 2) is counterintuitive, as thermal maturity  
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2749 908 should increase with depth (Peters et al., 2005, 1980). Furthermore, the Interbedded Evaporites  
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2751 909 exhibit mixed signals that include high values of the  $C_{31} \alpha\beta$  S/R ratio (indicative of thermally  
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2753 910 mature organic matter) in addition to  $C_{31}$  hopanes with the  $\beta\beta$  biological configuration (indicative  
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2755 911 of immature organic matter) (Fig. 11; Table 2). This aspect further supports the occurrence of  
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2757 912 organic matter mixtures from differing ages and thermal histories, i.e., a higher proportion of  
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2759 913 allochthonous, thermally mature organic matter in the Interbedded Evaporites compared with the  
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2761 914 Main Halite and Pre-Evaporite samples. This interpretation is consistent with similar trends  
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2763 915 observed in early Paleogene (Sepúlveda et al., 2009) and Quaternary (Rashid and Grosjean,  
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2765 916 2006) studies. Such trends may reflect an intensification of the hydrological cycle, and thus  
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2767 917 enhanced precipitation, continental runoff, and the transport of reworked, and pre-aged,  
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2769 918 continental or marginally-derived organic matter during the deposition of the Interbedded  
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2771 919 Evaporites. Another mechanism through which transport can occur is dense shelf-water  
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2773 920 cascading (DSWC) transport of sediment and associated organic matter from marginal settings to  
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2775 921 deep Mediterranean basins, as reported to occur in the Mediterranean today (Canals et al., 2009).  
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2777 922 The interpretation of transport in these intervals is consistent with the occurrence of clastic  
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2779 923 material, larger sub-rounded minerals, and re-worked Cretaceous and Eocene foraminifera within  
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2781 924 samples from the Interbedded Evaporites, which also supports the presence of reworked, older  
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2783 925 sediments. Both Cretaceous and Eocene organic-rich source rocks are known around the  
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2785 926 Mediterranean Basin (e.g., Almogi-Labin et al., 1993; Bayliss, 1973; Meilijson et al., 2014), and  
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2787 927 might represent sources of pre-aged weathered and transported organic matter, matching the  
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2789 928 apparent higher maturity measured from the organic-matter extract of the Interbedded Evaporites  
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2791 929 sediments.  
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2803 930 In summary, the similarities between our data and of Vasiliev et al. (2017) suggest that  
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2805 931 organic geochemical analysis from the Dolphin well might be used as regional  
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2807 932 chemostratigraphic markers to distinguish between Pre-Evaporites and Argillaceous Diatomites  
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2809 933 sediments, and the overlying Interbedded and Argillaceous Evaporites. A correlation between  
2810  
2811 934 MSC stage 3 and the upper part of the MSC in the Levant Basin has been previously proposed  
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2813 935 based on seismic interpretation and the sampling of shallower deposits (Druckman et al., 1995;  
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2815 936 Gvirtzman et al., 2017; Lugli et al., 2013). Here, we present evidence supporting the occurrence  
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2817 937 of stage 2 sea-level drawdown or stage 3 and ‘Lago-Mare’-type deposits in the deep domains of  
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2819 938 the Eastern Mediterranean. This includes increased supply of clastic material into the basin,  
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2821 939 reworked fauna, and chemostratigraphic markers (Figs 3, 9 and 10).  
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### 2825 940 **5.3 From cycles to astronomical tuning**

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2827  
2828 941 Cyclostratigraphy and astronomical tuning of sediment sections, geochemical signals, and  
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2830 942 well-log responses have been extensively used for stratigraphic interpretations of MSC deposits  
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2832 943 across the Mediterranean (Dela Pierre et al., 2014; Hilgen et al., 2007, 2000, 1995; Hilgen and  
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2834 944 Krijgsman, 1999; Hüsing et al., 2010, 2009, Krijgsman et al., 2001, 1999, 1997; Lugli et al.,  
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2836 945 2015; Manzi et al., 2015, 2013, 2012; Ochoa et al., 2015; Topper et al., 2014). The CIESM  
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2838 946 stratigraphic model of the MSC has halite deposited in stage 2 of the MSC, during four  
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2840 947 precession cycles (e.g., Roveri et al., 2014a, with reference to Laskar et al., 2004; Fig. 12). These  
2841  
2842 948 are part of the 32 precession-controlled cycles (Laskar et al., 2004) identified across the  
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2844 949 Mediterranean, with a periodicity of about 20 kyr per cycle, amounting to the 640 kyr time frame  
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2846 950 of the MSC. Manzi et al. (2015) proposed to tune the high-reflectivity intervals in the seismic  
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2848 951 section of the Levant (interpreted as clastic units; Gvirtzman et al., 2013a) to summer insolation  
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2850 952 maxima, and the transparent intervals (interpreted as halite) to summer insolation minima, within  
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2859 953 these four insolation cycles. By contrast, the study of the Pre-Evaporites in the Dolphin well by  
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2861 954 Meilijson et al. (2018) and the results of this study suggest that salt formation began around 5.97  
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2863 955 Ma, i.e., more or less synchronously with the marginal deposition of the PLG. According to this  
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2865 956 age model, the evaporitic sequence in the Levant Basin (Fig. 12) was deposited between 5.97 and  
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2867 957 5.33 Ma, corresponding to a time span of ~640 kyr rather than 50 kyr, and encompassing 32  
2868  
2869 958 insolation cycles (Laskar et al., 2004). Our suggested scenario would imply an average cycle  
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2871 959 thickness of ~50 m, as the studied section is 1590 m thick.

2874 960 Bandpass filtering of the Dolphin well logs resulted in the identification of 31 cycles, closely  
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2876 961 matching the 32 precession-controlled cycles (Laskar et al., 2004) in the interval between 5.97  
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2878 962 and 5.33 Ma. However, this age model includes several assumptions: (1) the evaporite record at  
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2880 963 the studied site is complete with no hiatus, (2) it is largely undisturbed by salt tectonics, and (3)  
2881  
2882 964 the sedimentation rate is approximately constant, with no significant changes between the halite-  
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2884 965 rich intervals and clastic-diatomitic intervals. The Dolphin record lacks chronostratigraphic tie  
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2886 966 points and contains intervals in which the log data are erratic (Figs 5, S2). Furthermore, the  
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2888 967 Dolphin well area appears deformed in the upper part of the section, and Unit 6 is missing  
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2890 968 (overlying the Interbedded Evaporites; Fig. 6). These sources of uncertainty suggest that the  
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2892 969 Dolphin well spectral analysis provides a first order approximation of the number of cycles,  
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2894 970 primarily across the lower part of the section. However, the large number of cycles observed in  
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2896 971 the Main Halite interval, if assumed to reflect precessional cycles, suggests a longer period of  
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2898 972 deposition than ~50 kyr. The Leviathan-1 well is much less deformed (Figs 5, 6) and has a thick  
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2900 973 interval of Unit 6 (Gvirtzman et al., 2013; 2017), similar to the sequence at the Aphrodite well  
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2902 974 (Manzi et al., 2018). It also presents a good fit between the seismic and the RE well-log  
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2904 975 response. The observed regularity produced a filtered cycles curve (Fig. 5), which reveals a good  
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2915 976 fit with the well log curve. We hypothesize that these cycles represent the 32 precession cycles  
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2917 977 identified in MSC sections across the Mediterranean. This would imply that the Main Halite  
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2919 978 interval in the lower part of the studied section is equivalent to stage 1 (PLG) in marginal  
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2922 979 sections, as also proposed by Meilijson et al. (2018).  
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2924 980 However, lacking chronostratigraphic tie points in the evaporitic section, an alternative  
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2926 981 explanation for the cyclicity observed in the well logs of the halite and the seismic profiles  
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2928 982 should be considered to reconcile the age model suggested by Manzi et al. (2018) for the Levant  
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2930 983 Basin. In this model the FBI unit, which represents the uppermost part of the Pre-Evaporites in  
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2932 984 the Aphrodite well, corresponds to MSC stage 1 (the PLG; Manzi et al., 2018), while the  
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2934 985 uppermost part of the section corresponds to stage 3 (Unit 7; Gvirtzman et al., 2017). Following  
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2936 986 this model, the ~33 cycles identified within the Leviathan-1 MSC section (Figs 5, 7) correspond  
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2938 987 to the ~50 kyr estimated for the duration of stage 2 of the MSC (Roveri et al., 2014), and have  
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2940 988 therefore a cycle duration of ca. 1560 years. If we take into account the likely different  
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2942 989 sedimentation rates of the Argillaceous Diatomites facies, this period could correspond to the  
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2944 990 period inferred for the Dansgaard-Oescher events (1470 years), as observed during the second  
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2946 991 half of the last glacial (Schulz, 2002) (although see comments by Ditlevsen et al. (2007) and  
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2948 992 Lohmann and Ditlevsen (2018) on the validity and interpretation of these cycles). Alternatively,  
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2950 993 they could be explained by the Bond cycles, as observed for the North Atlantic during the  
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2952 994 Holocene (1500 years; Bond et al., 2001). Another alternative are the periods of ca. 1000 years  
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2954 995 corresponding to the so-called Eddy cycle observed in the  $^{14}\text{C}$  record, which relate to variations  
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2956 996 in solar activity (Steinhilber et al., 2012). However, this last alternative is unlikely: if the regular  
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2958 997 alternations in the halite would correspond to Eddy cycles, it implies that stage 2 of the MSC  
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998 lasted only ~32 kyr. This means that the climax stage of the MSC cannot encompass both glacial  
999 stages TG14 and 12 (Fig. 12), as is assumed in the CIESM model.

1000 In the Realmonte salt mine in Sicily, 10-15 cm alternations in the salt have been interpreted as  
1001 annual cycles (Manzi et al. 2012). Such sedimentation rates of ca. 10 cm/yr would imply that the  
1002 1,060 m thick Main Halite interval in the Levant could have been formed in a short time period  
1003 of 10,600 years, although average sedimentation rate may be lower in the Argillaceous  
1004 Diatomites. However, it is hard to reconcile such a short duration of deposition with the amounts  
1005 of halite required to build up the thickness of the Levant Basin halite layer.

1006 In the absence of a simple explanation for the cyclicity observed in the Dolphin well, we now  
1007 consider its interpretation in relation to the different elements of the CIESM model for marginal  
1008 MSC deposits. The CIESM (2008) consensus stratigraphic model for the MSC is strongly based  
1009 on astronomical tuning of different MSC sections and includes the following division of the 32  
1010 orbital-related cycles identified during this time frame (Laskar et al., 2004): cycles 1-18 in stage  
1011 1 (PLG), 19-23 in stage 2 (RLG), 24-28 in stage 3.1 (lower part of Upper Gypsum), and 29-32 in  
1012 stage 3.2 (the Lago Mare). The correlation between the Levant MSC well-log-based  
1013 astrochronology, the orbital target curves, and the chronology of shallow to marginal sections  
1014 (CIESM, 2008) of the MSC indicates the following: (1) the Main Halite interval (3759-2800 m  
1015 in the Leviathan-1 well) is bound between the Levant filtered cycles 1 through 19 (Fig. 12). A  
1016 comparison with the current MSC chronology (CIESM, 2008; Roveri et al., 2014a) shows a  
1017 correlation with the number of cycles in the interval between 5.97 and 5.6 Ma from the base of  
1018 the PLG (stage 1) to the base of the RLG (stage 2); (2) the Interbedded Evaporites interval  
1019 (2800-2320 m) is bound between the Levant filtered cycles 19 through 28 (Fig. 12), which  
1020 correlates to the number of cycles in in stage 2 (the RLG; 5.6-5.55 Ma; cycles 19-23), with its



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3027 1021 top known as the ‘top salt’ horizon, and the lower part of stage 3 (stage 3.1 the Upper Gypsum  
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3029 1022 who’s base is at 5.42 Ma). Thus, the lower part of the Interbedded Evaporites is also equivalent  
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3032 1023 to stage 2 halite deposits recognized in intermediate basins, such as the Realmonte salt mine in  
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3034 1024 Sicily; (3) at the upper part of the Interbedded Evaporite and the Argillaceous Evaporites interval  
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3036 1025 are equivalent to stage 3 of the MSC (2320-2090 m; Fig. 12), ending with the clastic Lago-Mare  
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3038 1026 interval.

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3040 1027 Following the suggestion of Meilijson et al. (2018) for an early onset of halite deposition in  
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3042 1028 the deep Mediterranean basins, similar claims were made by García-Veigas et al. (2018) based  
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3044 1029 on sulfur stable-isotopes analysis of marginal and intermediate basin gypsum deposits. They  
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3046 1030 hypothesize that the deep-basin halite deposits are not equivalent to one phase of deposition  
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3049 1031 during stage 2 of the MSC, but rather comprise two to three phases of halite deposition,  
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3051 1032 beginning with halite deposition during stage 1 of the MSC. Our astronomical tuning agrees with  
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3053 1033 this idea by positioning the boundary between stage 1 and 2 of the MSC (2762 m in the Dolphin  
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3055 1034 well, 2800 m in Leviathan-1) at the top of the Main Halite interval. Consequently, we propose  
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3057 1035 that the Main Halite is equivalent to stage 1 gypsum deposits of the PLG, as indicated  
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3059 1036 independently by the diatomite facies. The increase in clastic and reworked faunal material into  
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3061 1037 the basin fits well with our astrochronology, placing the Interbedded Evaporites within the time  
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3063 1038 period of the Reworked Lower Gypsum (stage 2 of the MSC). Sea-level drawdown promoted the  
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3066 1039 scraping of the shelf, reshaping of drainage and transport systems across the basin, and  
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3068 1040 redepositing of vast amounts of eroded sediment into the intermediate basins. It also delivered  
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3070 1041 vast amounts of fine-grained material to the deep basins, as observed in the Interbedded  
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3072 1042 Evaporites in the Levant Basin. Lastly, the identification of the *Discoaster quinqueramus* in Unit  
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3083 1043 5 (the Interbedded Evaporites) by Manzi et al. (2018) supports this conclusion, as this species  
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3085 1044 went extinct towards the end of stage 2.  
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#### 3088 1045 **5.4 Implications of a new MSC chronology in the Mediterranean**

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3091 1046 While not conclusive, the integration of our different stratigraphic proxies supports an early  
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3093 1047 and long-lasting deposition of deep-basin halite. The direct implication of this age model is that  
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3095 1048 halite was deposited in the deep Eastern Mediterranean when sea level was high and partial,  
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3097 1049 episodic connection with the Atlantic still prevailed (Dela Pierre et al., 2014; Flecker and Ellam,  
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3099 1050 2006; Krijgsman et al., 2002; Roveri et al., 2014b), synchronously with gypsum deposition along  
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3101 1051 the Mediterranean margins and intermediate basins (Ochoa et al., 2015). Our results do not  
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3103 1052 exclude an evaporative drawdown (e.g., Lofi, et al., 2011; Rouchy and Caruso, 2006; Ryan,  
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3105 1053 2008) and lower sea level at the acme of the MSC during stage 2 (Ohneiser et al., 2015). The  
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3107 1054 lack of sedimentological features within the monotonously clean halite, and our interpretation of  
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3109 1055 long-lasting deep-water evaporite depositional settings, indicate that salt must have started to  
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3111 1056 precipitate within a deep-basin deep-water environment, and not in shallow waters. We propose  
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3113 1057 that sea-level drawdown prompted enhanced transport of clastic sediments into the deep basin  
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3115 1058 resulting in the deposition of the Interbedded Evaporites unit, analog to the marginal deposition  
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3117 1059 of the RLG. Studies of strontium isotopes from the Lower Evaporites (PLG, MSC stage 1)  
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3119 1060 consistently report isotopic values close to those characteristic of the global ocean (Flecker and  
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3121 1061 Ellam, 2006; Roveri et al., 2014b), and do not support an early desiccation model (Cita, 1976;  
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3123 1062 Hsü, 1973). While advocating a different chronological model, our study is consistent with these  
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3125 1063 interpretations and shows that halite deposition started during a time when Atlantic inflow was  
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3127 1064 still evident.  
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1065 A coeval initiation of basinal halite and marginal gypsum precipitation calls for a reevaluation  
1066 of previous models for MSC development, as well as its effect on global ocean salinity and  
1067 climate. We refer to the timing and persistence of halite deposition (which may have been an  
1068 order of magnitude larger than previously thought), and also to the substantially lower rates of  
1069 deposition of the deep-basin salt unit, from a previous assumption of 3,000 cm/kyr (according to  
1070 CIESM chronology) to 250 cm/kyr as deduced from our new age model. Although this assumes  
1071 continuous precipitation and no dissolution, which we consider unlikely if the water is being  
1072 relatively refreshed with additional seawater throughout deposition. The Levant  
1073 chronostratigraphic model suggests that steady state of halite deposition was achieved and  
1074 maintained earlier in the MSC than previously thought. Both halite and gypsum could have been  
1075 precipitated synchronously, with their partitioning possibly governed by their different solubility  
1076 product constants ( $K_{sp}$ ) and ion availability. Furthermore, if we allow for an order of magnitude  
1077 change in the time scale of halite precipitation, then the required sedimentation flux that removes  
1078 sodium and chlorine from seawater is reduced. This exercise substantially reduces the total sea-  
1079 level drawdown (Ryan, 2008) required to explain the deposition of a ~2 km-thick salt deposit. A  
1080 further possible mechanism to explain the synchronous deposition of gypsum and halite in  
1081 marginal and deeper parts of the basin, respectively, includes density stratification and down-  
1082 shelf cascading of brines (Roveri et al., 2014c; Sirota et al., 2017). While salt-saturated shallow  
1083 waters seem to have reached gypsum saturation values, brine formation might have continuously  
1084 flowed down-shelf, in a similar manner as dense shelf-water cascading (DSWC) is observed  
1085 today around the Mediterranean Basin (Canals et al., 2009, 2006). DSWC is associated with  
1086 mass-transport complexes and submarine channels, and has a significant impact on the sediment  
1087 and organic-matter supply from continental and shallow-marine settings to deep-sea ecosystems.

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3195 1088 Mass-balance calculations suggest that the input of dissolved organic carbon and suspended  
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3197 1089 particulate organic carbon from ocean margins to the open ocean interior may be more than an  
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3200 1090 order of magnitude greater than direct inputs of organic carbon produced near the ocean surface  
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3202 1091 today (Bauer and Druffel, 1998). Similarly, highly saturated waters produced in an evaporitic  
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3204 1092 Mediterranean may have produced vast quantities of brine accumulating in the deep depocenters.  
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3206 1093 Brine formation may have been at least partly controlled by precession-induced increases in river  
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3208 1094 runoff (Marzocchi et al., 2015), and potentially by surface inflow from the Paratethys  
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3210 1095 (Karakitsios et al., 2017; Krijgsman et al., 2010). Salinity stratification is supported by  
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3212 1096 geochemical evidence for the occurrence of low-salinity surface waters overlying deep brines at  
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3214 1097 gypsum and halite saturation (Christeleit et al., 2015), as well as by the presence of brackish-  
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3216 1098 water faunas of Paratethyan origin in the Lago-Mare phase (Stoica et al., 2016). Our data,  
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3218 1099 including high concentrations of long-chain *n*-alkanes (Table 1) and high LCA/SCA values  
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3220 1100 (Table 1), also support the occurrence of increased river runoff into the basin during the  
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3222 1101 deposition of the Interbedded Evaporites.

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3225 1102 Our interpretation of a deep-basin deep-water model and early onset of halite, rejuvenates an  
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3227 1103 idea that has been a focus of debate in the past (e.g., Garcia-Castellanos and Villaseñor, 2011;  
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3229 1104 Lofi et al., 2011; Ryan, 2008; Schmalz, 1969). Simon and Meijer (2017) used a box-model setup  
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3231 1105 to model the MSC events forced by Atlantic exchange and evaporative loss. This model  
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3233 1106 demonstrated that a significantly stratified Mediterranean water column could have been  
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3235 1107 established early in the crisis, while the duration of halite deposition must have taken longer than  
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3237 1108 currently considered in the MSC stratigraphic consensus model. The synchronous formation of  
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3239 1109 gypsum and halite in proximal and distal basins, respectively, could have occurred at different  
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3241 1110 levels within the basin, with lower rates of halite sedimentation than previously thought. Our  
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1111 data support the model by Simon and Meijer (2017) and calls to reevaluate Mediterranean MSC  
1112 sections, while considering a possible early deposition of halite.

1113 Sea-level drop during stage 2 of the MSC may have added more proximal basins to the  
1114 regional deep-sea deposition of halite, which might explain why those intermediate-basin halite  
1115 deposits correlate to the stage 2 RLG. Such a mechanism can explain the existence of marginal  
1116 or intermediate-depth basins with relatively thin halite deposits, which only correlate with the  
1117 Interbedded Evaporites interval in the Levant (Fig. 12), in which halite is still the dominant  
1118 lithology. For example, the marginal Realmonte salt mine has a ~600 m thick halite sequence  
1119 (Lugli et al., 1999; Roveri et al., 2014a) compared with the thick (>2 km) halite deposits in deep  
1120 Mediterranean basins. In a similar manner, recent studies from the Dead Sea demonstrate  
1121 downslope-flowing brines, in which the deep basal areas accumulate the most brine and the  
1122 marginal areas are influenced by fresher waters and hence subject to more dissolution (Sirota et  
1123 al., 2016).

1124 Being one of the largest and youngest salt giant formation episodes in Earth's history, the  
1125 MSC is repeatedly used as a cornerstone for explaining evaporite deposition. Our new model,  
1126 which includes the synchronous deposition of sulfates in the margins of the basin and halite at its  
1127 center, calls for a re-evaluation of the mechanisms governing evaporite deposition in other salt-  
1128 giant deposits in the geologic record. For example, in the Permian Zechstein, similar to the  
1129 Mediterranean, sulfates appear to have been limited to the margins while halite was deposited in  
1130 the deeper parts of the basin (Richter-Bernburg, 1985). This is also the case for the Permian  
1131 Delaware Basin in Texas and New Mexico, where clear inter-fingering between sulfates and  
1132 halite are observed as brine concentrations oscillate (Anderson and Dean, 1995).

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3307 1133 The alternating clastic and evaporitic sediments of the Interbedded Evaporites (Unit 5;  
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3309 1134 Gvirtzman et al., 2013; 2017) include cycles 19-28, matching in its lower part the time frame of  
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3312 1135 MSC stage 2, the RLG. Isolation from the Atlantic and significant sea-level drawdown are  
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3314 1136 proposed as the formation mechanism for both the onshore deep subaerial canyons and offshore  
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3316 1137 erosion surfaces across the Mediterranean (Lofi et al., 2011; Ryan, 1976; Ryan and Cita, 1978).  
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3318 1138 Different models were proposed to explain the mechanisms behind erosion, transport, and re-  
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3320 1139 deposition, such as early subaqueous large-scale mass-wasting processes occurring at the  
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3322 1140 beginning of the MSC drawdown, subaerial rivers down-cutting by retrogressive action to adjust  
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3324 1141 for their new base level, or marine abrasion as possible agent for late erosion (Lofi et al., 2011  
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3326 1142 and references therein). Regardless of the mechanism, clastic geometries are clear in MSC  
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3328  
3329 1143 seismic sections and are partly controlled by local factors such as the dimension of the drainage  
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3331 1144 basin, resulting in major differences between the Messinian sedimentary successions in the  
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3333 1145 different areas of the Mediterranean. The whereabouts of the massive products of these basin-  
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3335 1146 wide erosional processes has been one of the MSC's enigmas (Ryan, 1976; Ryan and Cita, 1978;  
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3337 1147 Lofi et al., 2011). The seismic facies defined as the Complex Unit (CU; Lofi et al., 2011) in the  
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3339 1148 Western Mediterranean is either chaotic or roughly bedded, and is believed to account for some  
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3341 1149 of the waste products. CU deposits are absent on the margin shelves, rarely observed on the  
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3343 1150 upper slopes, and mainly observed along the base of the slopes, either as fan-shaped deposits at  
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3345  
3346 1151 the Messinian river mouths or as poorly organized bodies elsewhere. This unit marks the  
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3348 1152 transition between the eroded slopes and deep-basin deposits (Lofi et al., 2011). The CU is  
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3350 1153 positioned above or parallel to the Mobile Unit (the halite).

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3352 1154 In summary, stage 2 of the MSC is characterized by massive sediment displacement, for  
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3354 1155 which only a portion is accounted for. We propose that the Interbedded Evaporites (Unit 5;  
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3363 1156 Gvirtzman et al., 2017) are part of this high-energy system and that the interbedding of clastics  
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3365 1157 represents the deep-basin depocenters for the fine grained material at the distal part of the  
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3367  
3368 1158 drainage system. These precession-controlled clastic incursions reached into an evaporitic  
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3370 1159 system, which in the deep basins has been depositing halite for ~360 kyr during stage 1 of the  
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3372 1160 MSC. We argue that this idea could not be examined before due to lack of a sedimentary record  
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3374 1161 from the deep basin and the difficulty of correlating marginal and deep-basin units based on  
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3376 1162 seismostratigraphy. The call for caution regarding the interpretation of MSC-related offshore  
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3378 1163 data was recently presented by Roveri et al. (2019). They pointed out that MSC units with  
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3380 1164 different age, nature and depositional setting, may show similar seismic facies and geometries.  
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3382 1165 On the other hand, the same unit may appear as belonging to different seismic facies, either with  
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3384 1166 parallel and high-amplitude reflections or even transparent or chaotic reflectivity due to seismic  
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3386 1167 interference patterns related to the dominant frequency. We therefore argue against lumping the  
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3388 1168 different facies of the Interbedded Evaporites into a unified deep-basin halite deposit,  
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3390 1169 disregarding its clastic nature, as done in past interpretations of the Levant Basin MSC section  
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3392 1170 (e.g., Manzi et al., 2018). Here we offer new sedimentological analysis of the non-evaporitic  
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3394 1171 facies, interpreted in the past as clastic deposits through seismic and well-log interpretation (e.g.,  
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3396 1172 Feng et al., 2016). We argue that two different ‘non-halite’ deposits exist in the Levant deep  
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3398 1173 MSC deposits: 1) the mostly biogenic remains of diatoms (the Argillaceous Diatomites) within  
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3400 1174 the stage 1 Main Halite interval, and 2) the clastic and reworked deposits of the Interbedded  
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3402 1175 Evaporites/Argillaceous Evaporites belonging to stage 2 and 3 of the MSC.  
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3404 1176 Stage 3 of the MSC is generally characterized by reworking of shelf sediments and their  
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3406 1177 occasional influx into the basin during renewed gypsum deposition. We position the base of  
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3408 1178 stage 3 within the Interbedded Evaporites at cycle 23 (Figs 5, 6, 12), pointing to a much thicker  
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3419 1179 stage 3 section in the Levant than in the model of Gvirtzman et al. (2017), Manzi et al. (2018), or  
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3421 1180 Madof et al. (2019). Relying on the CIESM (2008) stratigraphic model, these separate studies  
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3423 position the halite into stage 2, and continue stage 2 until almost the top of the Levant MSC  
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3425 section. They position stage 3 at the topmost part of the section, represented only by Unit 7 - a  
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3427 thin anhydrite and shale unit (interpreted by well-log data in the deep basin as no study has  
3428 1183  
3429 recovered samples from this interval thus far). These studies mainly differ in their interpretation  
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3431 of the stage 3 depositional environment, namely subaerial (Madof et al., 2019) or subaqueous  
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3433 (Gvirtzman et al., 2017) dissolution and truncation. According to our depositional model (Fig.  
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3435 12), Unit 6 belongs to stage 3 of the MSC (the Upper Gypsum and Lago Mare; CIESM, 2008),  
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3437 and the IMTS (Gvirtzman et al., 2017) or IES (Madof et al., 2019) unconformities in the Levant  
3438 1188  
3439 represent the transition between stage 3.1 (Upper Gypsum) and 3.2 (Lago Mare) of the MSC.  
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3441 The latter stage (3.2) was attributed to Unit 7 and perhaps also to parts of the overlying brackish  
3442 1190  
3443 Afq Formation (Druckman et al., 1995) by Gvirtzman et al. (2017). The introduction of  
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3445 Paratethyan waters and sediment, termed Lago Mare deposits along the Paratethyan side of the  
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3447 Mediterranean, is also likely to have reached the deep basins. However, while those might have  
3448 1193  
3449 reached the Levant Basin, different local drainage systems are most likely the sources for the  
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3451 MSC stage 3 transported sediments in the Levant area. A local source for transported sediments  
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3453 is the Nile drainage and fan systems, identified as reaching further northwest, beyond the  
3454 1196  
3455 Dolphin and Leviathan wells, towards the Eratosthenes Seamount offshore Cyprus (Hawie et al.,  
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3457 2013a, 2013b). In addition, local drainage systems that may have supplied the transported  
3458 1198  
3459 sediments include the Afq and Ashdod canyons (Bertoni and Cartwright, 2007; Druckman et al.,  
3460 1199  
3461 1995), and the southern Turkey and western Syria drainage systems proposed by Madof et al.  
3462 1200  
3463 (2019).  
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3475 1202 **6. Conclusions**  
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3478 1203 Over the past 50 years, models explaining the formation of offshore MSC deposits have  
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3480 1204 remained hypothetical in the absence of a complete sedimentary record of the deep  
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3482 1205 Mediterranean Basin. The current study presents results from the offshore Dolphin and  
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3484 1206 Leviathan-1 wells, which penetrated MSC evaporites from 2025 to 3616 m, and from 2090 to  
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3486 1207 3759 m, respectively. Our results challenge some of the current models for the MSC regarding  
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3488 1208 the synchronicity or diachronism of evaporite deposits across the Mediterranean Basin, their  
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3490 1209 composition, and controlling factors. A longer duration for halite deposition than previously  
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3492 1210 assumed impacts our understanding of the biochemical and spatial constraints of this time period.  
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3494 1211 While similar ideas have been previously raised (e.g., Van Couvering et al., 1976; Govers, 2009;  
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3496 1212 Hardie and Lowenstein, 2004; Meilijson et al., 2018; Ryan, 2011; Simon and Meijer, 2017), we  
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3498 1213 provide the first report on sedimentological data from the deep basin MSC halite deposits  
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3500 1214 supporting the scenario of long-lasting salt deposition. We call for a re-evaluation of models  
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3502 1215 based on a ~50 kyr-long deposition of halite in the deep basins. However, samples from the  
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3504 1216 upper part of the deep MSC deposits in the Eastern Mediterranean are not yet available, while  
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3506 1217 the existing sedimentary record drilled by the industry consists of well cuttings and not a  
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3508 1218 continues core. The complexity revealed by this study makes a strong case for future scientific  
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3510 1219 drilling efforts that can retrieve cores from different parts of the deep-basin halite deposits of the  
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3512 1220 Mediterranean.  
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3516 1221 This study aimed at addressing the composition and key stratigraphic questions regarding the  
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3518 1222 timing and correlation of MSC events in the deep Mediterranean. Our main findings can be  
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3520 1223 summarized as follows:  
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- 1224 1. The formation of thick halite deposits in the Levant Basin occurred in a deep-basin deep-
- 1225 water environment that began earlier than previously thought, during the PLG phase of
- 1226 gypsum precipitation in the marginal basins. This implies that a shallow desiccated
- 1227 scenario is not necessarily required to generate halite precipitation during the MSC. The
- 1228 presence of well-preserved marine planktonic diatoms within the massive halite deposits
- 1229 strongly supports a periodic connectivity between the Atlantic and the Eastern
- 1230 Mediterranean during halite deposition.
- 1231 2. The exact timing for the end of deep-basin halite precipitation is still unclear. Well-log
- 1232 interpretation, cyclostratigraphy, and the astronomical tuning model presented here
- 1233 suggest that halite deposition continued at least until 5.45 Ma, and interbedded clastic
- 1234 material and evaporites (probably mainly gypsum/anhydrite) persisted until ca. 5.33 Ma.
- 1235 3. The transition into the Interbedded Evaporites interval at 2560 m at Dolphin and 2800 m
- 1236 at Leviathan-1 marks a major shift in the mode of deposition. An increase in basin-ward
- 1237 transport of sediments is indicated by the high abundance of larger sub-rounded clastic
- 1238 grains such as quartz and plagioclase, clay, micrite, and reworked Cretaceous to Eocene
- 1239 benthic and planktic foraminifera. Variable thermal maturity indices also point to mixed
- 1240 sources of organic matter. In general, biomarker indices in the Interbedded Evaporites
- 1241 resemble those measured elsewhere in the Mediterranean Basin from strata with
- 1242 transported material and mixed sources. The transition from the Main Halite to the
- 1243 Interbedded Evaporites at 2560 m most likely represents the transition between stage 1
- 1244 and 2 of the MSC. The large amounts of clastic sediments in the Interbedded Evaporites
- 1245 are possibly an answer to one of the MSC enigmas regarding the location of the

3585  
3586  
3587 1246 transported material related to the sea-level drawdown of stage 2 and the interruption of the  
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3589 1247 connection with of the Atlantic Ocean.

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3592 1248 4. During the MSC, high sea level and partial connectivity with the global ocean promoted  
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3594 1249 the deposition of deep-basin deep-water halite, while see-level drawdown promoted  
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3596 1250 deposition of reworked and transported material from the margins into deep  
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3598 1251 Mediterranean basins.

3600  
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1266 **References**

1267 Alinat, J., Cousteau, J., 1962. Accidents de terrain en mer de Ligurie. *Océanographie géologique*  
1268 et géophysique de la Méditerranée occidentale, 121. Centre national de la recherche  
1269 scientifique, Paris.

1270 Almogi-Labin, A., Bein, A., Sass, E., 1993. Late Cretaceous upwelling system along the  
1271 Southern Tethys Margin (Israel): Interrelationship between productivity, bottom water  
1272 environments, and organic matter preservation. *Paleoceanography* 8, 671–690.  
1273 doi:10.1029/93PA02197

1274 Anderson, R.Y., Dean, W.E., 1995. Filling the Delaware Basin: Hydrologic and Climatic  
1275 Controls on the Upper Permian Castile Formation Varved Evaporite, in: Scholle, P.A.,  
1276 Peryt, T.M., Ulmer-Scholle, D.S. (Eds.), *The Permian of Northern Pangea: Volume 2:*  
1277 *Sedimentary Basins and Economic Resources*. Springer Berlin Heidelberg, Berlin,  
1278 Heidelberg, pp. 61–78. doi:10.1007/978-3-642-78590-0\_4

1279 Arnon, A., Selker, J.S., Lensky, N.G., 2016. Thermohaline stratification and double diffusion  
1280 diapycnal fluxes in the hypersaline Dead Sea. *Limnol. Oceanogr.* 61, 1214–1231.  
1281 doi:10.1002/lno.10285

1282 Bauer, J.E., Druffel, E.R.M., 1998. Ocean margins as a significant source of organic matter to  
1283 the deep open ocean. *Nature* 392, 20–23. doi:10.1038/33122

1284 Bayliss, D.D., 1973. *Micropalaeontology of sections Cenomanian to Middle Eocene West Bank*  
1285 *of Jordan*. London.

1286 Bellaiche, G., Genesseeux, M., Mauffret, A., Rehault, J.P., 1974. Prélèvements systématique et  
1287 caractérisation des réflecteurs acoustiques: nouvelle étape dans la compréhension de la  
1288 géologie de la Méditerranée occidentale. *Marine Geology* 16, M47–M56.

3697  
3698  
3699 1289 Berggren, W.A., Kennett, J.P., Srinivasan, M.S., 2006. Neogene Planktonic Foraminifera: A  
3700  
3701 Phylogenetic Atlas. *Micropaleontology*. doi:10.2307/1485586  
3702 1290  
3703  
3704 1291 Bertoni, C., Cartwright, J.A., 2007. Major erosion at the end of the Messinian Salinity Crisis:  
3705  
3706 Evidence from the Levant Basin, Eastern Mediterranean. *Basin Res.* 19, 1–18.  
3707  
3708 1293 doi:10.1111/j.1365-2117.2006.00309.x.  
3709  
3710 1294 Bertoni, C., Cartwright, J.A., 2006. Controls on the basinwide architecture of late Miocene  
3711  
3712 (Messinian) evaporites on the Levant margin (Eastern Mediterranean). *Sediment. Geol.*  
3713 1295  
3714 188–189, 93–114. doi:10.1016/j.sedgeo.2006.03.019.  
3715 1296  
3716  
3717 1297 Biehl, B.C., Reuning, L., Strozyk, F., Kukla, P.A., 2014. Origin and deformation of intra-salt  
3718  
3719 sulphate layers: An example from the Dutch Zechstein (Late Permian). *Int. J. Earth Sci.*  
3720 1298  
3721 103, 697–712. doi:10.1007/s00531-014-0999-4  
3722 1299  
3723  
3724 1300 Blanc, P., 2000. Of sills and straits : a quantitative assessment of the Messinian Salinity Crisis.  
3725  
3726 *Deep. Res. I* 47, 1429–1460.  
3727  
3728 1302 Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-  
3729  
3730 Bond, R., Hajdas, I., Bonani, G., 2001. Persistent Solar Influence on North Atlantic Climate  
3731  
3732 During the Holocene. *Science* (80-. ). 294, 2130–2136.  
3733  
3734  
3735 1305 Borsetti,, A. M., Curzi, P. V., Landuzzi, V., Mutti, M., Ricci Lucchi, F., Sartori, R., Tomadin, L.,  
3736  
3737 Zuffa, G.G., 1990. Messinian and pre-Messinian sediments from ODP leg 107 Sites 652 and  
3738  
3739 654 in the Tyrrhenian Sea: sedimentological and petrographic study and possible  
3740  
3741 comparisons with Italian sequences, in: Kastens, K. A., Mascle, J., et al. (Ed.), *Proc. Ocean*  
3742 1308  
3743 *Drill. Program, 107 Sci. Results* 107, 169–186. doi:10.2973/odp.proc.sr.107.161.1990.  
3744 1309  
3745  
3746 1310 Bourcart, J., Boillot, G., Cousteau, J.Y., Gennesseaux, M., Klimek, C., 1958. Les sediments  
3747  
3748  
3749  
3750  
3751  
3752

3753  
3754  
3755 1311 profonds au large de la cote nicoise. Comptes Rendus de l'Academie des Sciences Paris  
3756  
3757 1312 147, 116.  
3758  
3759 1313 Bray, E.E., Evans, E.D., 1961. Distribution of n-paraffins as a clue to recognition of source beds.  
3760  
3761 Geochim. Cosmochim. Acta 22, 2–15. doi:10.1016/0016-7037(61)90069-2  
3762 1314  
3763  
3764 1315 Buchbinder, B., Zilberman, E., 1997. Sequence stratigraphy of Miocene-Pliocene carbonate-  
3765  
3766 1316 siliciclastic shelf deposits in the eastern Mediterranean margin (Israel): effects of eustasy  
3767  
3768 1317 and tectonics. Sediment. Geol. 112, 7–32.  
3769  
3770 1318 Camerlenghi, A., Aosis, V., Lofi, J., Hübscher, C., deLange, G., Flecker, R., Garcia-Castellanos,  
3771  
3772 1319 D., Gorini, C., Krijgsman, W., Lugli, S., Makovsky, Y., Manzi, V., McGenity, T., Pan, N.,  
3773  
3774 1320 2014. Uncovering a Salt Giant. Deep-Sea Record of Mediterranean Messinian Events  
3775  
3776 1321 (DREAM) multi-phase drilling project, in: EGU. Vienna, p. 1.  
3777  
3778 1322 Canals, M., Danovaro, R., Heussner, S., Lykousis, V., Puig, P., Trincardi, F., Calafat, A.,  
3779  
3780 Durrieu de Madron, X., Palanques, A., 2009. Cascades in Mediterranean Submarine Grand  
3781 1323  
3782 Canyons. Oceanography 22, 26–43. doi:10.5670/oceanog.2009.03  
3783 1324  
3784  
3785 1325 Canals, M., Puig, P., de Madron, X.D., Heussner, S., Palanques, A., Fabres, J., 2006. Flushing  
3786  
3787 1326 submarine canyons. Nature 444, 354–357. doi:10.1038/nature05271  
3788  
3789 1327 Christeleit, E.C., Brandon, M.T., Zhuang, G., 2015. Evidence for deep-water deposition of  
3790  
3791 1328 abyssal Mediterranean evaporites during the Messinian salinity crisis. Earth Planet. Sci.  
3792  
3793 Lett. 427, 226–235. doi:10.1016/j.epsl.2015.06.060  
3794 1329  
3795  
3796 1330 CIESM, 2008. The Messinian Salinity Crisis from mega-deposits to microbiology - A consensus  
3797  
3798 1331 report. N° 33. CIESM Work. Monogr. 7–10.  
3799  
3800 1332 Cita, M.B., 1976. Biodynamic effects of the messinian salinity crisis on the evolution of  
3801  
3802 1333 planktonic foraminifera in the mediterranean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 20,  
3803  
3804  
3805  
3806  
3807  
3808

3809  
3810  
3811 1334 23–42. doi:10.1016/0031-0182(76)90023-7  
3812  
3813 1335 Cita, M.B., Ryan, W.B.F., Kidd, R.B., 1978. Sedimentation rates in neogene deep-sea sediments  
3814  
3815 from the mediterranean and geodynamic implications of their changes, in: Initial Reports of  
3816 1336 the Deep Sea Drilling Project. pp. 991–1002.  
3817  
3818 1337  
3819  
3820 1338 Cita, M.B., Santambrogio, S., Melillo, B., Rogate, F., 2006. Messinian Paleoenvironments: New  
3821  
3822 1339 Evidence from the Tyrrhenian Sea (ODP Leg 107). Proc. Ocean Drill. Program, 107 Sci.  
3823  
3824 1340 Results 107, 211–227. doi:10.2973/odp.proc.sr.107.161.1990.  
3825  
3826 1341 Clauzon G., Suc, J.P., Gautier, F., Berger, A., Loutre, M.F., 1996. Alternate interpretation of the  
3827  
3828 1342 Messinian salinity crisis, controversy resolved? *Geology*, 24, 363-366. Doi: 10.1130/0091-  
3829  
3830 1343 7613  
3831  
3832  
3833 1344 Cornet, C., 1968. Le graben médian (zone A) de la Méditerranée occidentale pourrait être  
3834  
3835 1345 pontien. *Sommaire Société Géologique de France* 149.  
3836  
3837 1346 Couto, D. Do, Popescu, S., Suc, J., Melinte-dobrinescu, M.C., Barhoun, N., Gorini, C., Jolivet,  
3838  
3839 1347 L., Poort, J., Jouannic, G., Auxietre, J., 2014. Lago Mare and the Messinian Salinity Crisis :  
3840  
3841 1348 Evidence from the Alboran Sea Lago Mare and the Messinian Salinity Crisis : Evidence  
3842  
3843 1349 from the Alboran Sea (S . Spain). *Mar. Pet. Geol.* 52, 57–76.  
3844  
3845 1350 doi:10.1016/j.marpetgeo.2014.01.018  
3846  
3847  
3848 1351 Van Couvering, J.A., Berggren, W.A., Drake, R.E., Aguirre, E., Curtis, G.H., 1976. The terminal  
3849  
3850 1352 Miocene event. *Mar. Micropaleontol.* 1, 263–286.  
3851  
3852 1353 Debenedetti, A., 1982. The problem of the origin of the salt deposits in the mediterranean and of  
3853  
3854 1354 their relations to the other salt occurrences in the neogene formations of the contiguous  
3855  
3856 1355 regions. *Mar. Geol.* 49, 91–114.  
3857  
3858 1356 Dela Pierre, F., Clari, P., Natalicchio, M., Ferrando, S., Giustetto, R., Lozar, F., Lugli, S., Manzi,  
3859  
3860  
3861  
3862  
3863  
3864

3865  
3866  
3867 1357 V., Roveri, M., Violanti, D., 2014. Flocculent layers and bacterial mats in the mudstone  
3868  
3869 1358 interbeds of the Primary Lower Gypsum unit (Tertiary Piedmont basin, NW Italy): Archives  
3870  
3871 of palaeoenvironmental changes during the Messinian salinity crisis. *Mar. Geol.* 355, 71–  
3872 1359 87. doi:10.1016/j.margeo.2014.05.010  
3873  
3874 1360  
3875  
3876 1361 Derin, B., 2000. Stratigraphic and environments of deposition of Or South 1075–2090 m. Ramat  
3877  
3878 1362 Gan, Derin Consulting & Micropaleontological Services LTD, Internal Isramco Consultant  
3879  
3880 1363 Report 2/00.  
3881  
3882 1364 Ditlevsen, P.D., Andersen, K.K., Svensson, A., 2007. The DO-climate events are probably noise  
3883  
3884 1365 induced: Statistical investigation of the claimed 1470 years cycle. *Clim. Past* 3, 129–134.  
3885  
3886 1366 doi:10.5194/cp-3-129-2007  
3887  
3888  
3889 1367 Driussi, O., Maillard, A., Ochoa, D., Lofi, J., Chanier, F., Gaullier, V., Briaais, A., Sage, F.,  
3890  
3891 1368 Sierro, F., Garcia, M., 2015. Messinian Salinity Crisis deposits widespread over the  
3892  
3893 1369 Balearic Promontory: Insights from new high-resolution seismic data. *Mar. Pet. Geol.* 66,  
3894  
3895 1370 41–54. doi:10.1016/j.marpetgeo.2014.09.008  
3896  
3897 1371 Druckman, Y., Buchbinder, B., Martinotti, G.M., Tov, R.S., Aharon, P., 1995. The buried Afik  
3898  
3899 1372 Canyon (eastern Mediterranean, Israel): a case study of a Tertiary submarine canyon  
3900  
3901 1373 exposed in Late Messinian times. *Mar. Geol.* 123, 167–185. doi:10.1016/0025-  
3902  
3903 1374 3227(94)00127-7  
3904  
3905  
3906 1375 Ensminger, A., Joly, G., Albrecht, P., 1978. Rearranged steranes in sediments and crude oils.  
3907  
3908 1376 *Tetrahedron Letters.* 1575–1578. doi:https://doi.org/10.1016/S0040-4039(01)94608-8  
3909  
3910 1377 Feng, Y.E., Yankelzon, A., Steinberg, J., Reshef, M., 2016. Lithology and characteristics of the  
3911  
3912 1378 Messinian evaporite sequence of the deep Levant Basin, Eastern Mediterranean. *Mar. Geol.*  
3913  
3914 1379 376, 118–131. doi:10.1016/j.margeo.2016.04.004  
3915  
3916  
3917  
3918  
3919  
3920



3921  
3922  
3923 1380 Flecker, R., Ellam, R.M., 2006. Identifying Late Miocene episodes of connection and isolation in  
3924  
3925 1381 the Mediterranean-Paratethyan realm using Sr isotopes. *Sediment. Geol.* 188–189, 189–203.  
3926  
3927 doi:10.1016/j.sedgeo.2006.03.005  
3928 1382  
3929  
3930 1383 Flecker, R., et al., 2015. Evolution of the Late Miocene Mediterranean-Atlantic gateways and  
3931  
3932 1384 their impact on regional and global environmental change. *Earth-Science Reviews*, 150,  
3933  
3934 1385 365–392.  
3935  
3936 1386 Frey-Martinez, J., Hall, B., Cartwright, J., Huuse, M., 2007. Clastic Intrusion at the Base of  
3937  
3938 1387 Deep-water Sands: A Trap-forming Mechanism in the Eastern Mediterranean. *Sand Inject.*  
3939  
3940 1388 *Implic. Hydrocarb. Explor. Prod. AAPG Mem.* 87 49–63. doi:10.1306/1209849M873255  
3941  
3942 1389 Garcia-Castellanos, D., Villaseñor, A., 2011. Messinian salinity crisis regulated by competing  
3943  
3944 1390 tectonics and erosion at the Gibraltar arc. *Nature* 480, 359–363. doi:10.1038/nature10651  
3945  
3946 1391 García-Veigas, J., Cendón, D.I., Gibert, L., Lowenstein, T.K., Artiaga, D., 2018. Geochemical  
3947  
3948 1392 indicators in Western Mediterranean Messinian evaporites: Implications for the salinity  
3949  
3950 1393 crisis. *Mar. Geol.* 403, 197–214. doi:10.1016/j.margeo.2018.06.005  
3951  
3952 1394 Gardosh, M., Druckman, Y., Buchbinder, B., Rybakov, M., 2008. The Levant Basin Offshore  
3953  
3954 1395 Israel: Stratigraphy, Structure, Tectonic Evolution and Implications for Hydrocarbon  
3955  
3956 1396 Exploration - revised edition. Geological Survey of Israel report GSI/4/2008.  
3957  
3958 1397 Garrison, R.E., Schreiber, B.C., Bernoulli, D., Fabricius, F.H., Kidd, R.B., Mélières, F., 1978.  
3959  
3960 1398 Sedimentary Petrology and Structures of Messinian Evaporitic Sediments in the  
3961  
3962 1399 Mediterranean Sea, Leg 42A, Deep Sea Drilling Project, in: *Initial Reports of the Deep Sea*  
3963  
3964 1400 *Drilling Project 42, No. 1.* pp. 571–612.  
3965  
3966  
3967  
3968 1401 Geletti, R., Zgur, F., Del Ben, A., Buriola, F., Fais, S., Fedi, M., Forte, E., Mocnik, A., Paoletti,  
3969  
3970 1402 V., Pipan, M., Ramella, R., Romeo, R., Romi, A., 2014. The Messinian Salinity Crisis: New  
3971  
3972  
3973  
3974  
3975  
3976

3977  
3978  
3979 1403 seismic evidence in the West-Sardinian Margin and Eastern Sardo-Provencal basin (West  
3980  
3981 1404 Mediterranean Sea). *Mar. Geol.* 351, 76–90. doi:10.1016/j.margeo.2014.03.019  
3982  
3983  
3984 1405 Gennari, R., Manzi, V., Angeletti, L., Bertini, A., Ceregato, A., Faranda, C., Gliozzi, E.,  
3985  
3986 1406 Menichetti, E., Rosso, A., Roveri, M., Taviani, M., 2013. A shallow water record of the  
3987  
3988 1407 onset of the Messinian salinity crisis in the Adriatic foredeep (Legnagnone section,  
3989  
3990 1408 Northern Apennines). *NU SC. Palaeogeogr. Palaeoclimatol. Palaeoecol.*  
3991  
3992 1409 doi:10.1016/j.palaeo.2013.05.015  
3993  
3994 1410 Govers, R., 2009. Choking the Mediterranean to dehydration: The Messinian salinity crisis.  
3995  
3996 1411 *Geology* 37, 167–170. doi:10.1130/G25141A.1  
3997  
3998  
3999 1412 Gvirtzman, Z., Manzi, V., Calvo, R., Gavrieli, I., Gennari, R., Lugli, S., Reghizzi, M., Roveri,  
4000  
4001 1413 M., 2017. Intra-Messinian truncation surface in the Levant Basin explained by subaqueous  
4002  
4003 1414 dissolution. *Geology* 45, 4–7. doi:10.1130/G39113.1  
4004  
4005 1415 Gvirtzman, Z., Reshef, M., Buch-leviatan, O., Ben-avraham, Z., 2013a. Intense salt deformation  
4006  
4007 1416 in the Levant Basin in the middle of the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.*  
4008  
4009 1417 379, 108–119. doi:10.1016/j.epsl.2013.07.018  
4010  
4011 1418 Gvirtzman, Z., Reshef, M., Buch-Leviatan, O., Ben-Avraham, Z., 2013b. Intense salt  
4012  
4013 1419 deformation in the Levant Basin in the middle of the Messinian Salinity Crisis. *Earth Planet.*  
4014  
4015 1420 *Sci. Lett.* 379, 108–119. doi:10.1016/j.epsl.2013.07.018  
4016  
4017  
4018 1421 Hall, J.K., Udintsev, G.B., Odnikov, Y.Y., 1994. The bottom relief of the Levantine Sea, in  
4019  
4020 1422 *Geologic Structure of the Northeastern Mediterranean.* Krashennnikov, V. A., Hall, J.K.,  
4021  
4022 1423 pp. 5–32, Historical Productions-Hall Ltd., Jerusalem.  
4023  
4024 1424 Hall, J.K., Lippman, S., Gardosh, M., Tibor, G., Sade, A.R., Sade, H., 2015. A New Bathymetric  
4025  
4026 1425 Map for the Israeli EEZ: Preliminary Results. State of Israel, Ministry of National  
4027  
4028  
4029  
4030  
4031  
4032

4033  
4034  
4035 1426 Infrastructure Energy and Water, Jerusalem.  
4036  
4037 1427 Hardie, L.A., Lowenstein, T.K., 2004. Did the Mediterranean Sea Dry Out During the Miocene?  
4038  
4039 a Reassessment of the Evaporite Evidence From Dsdp Legs 13 and 42a Cores. *J. Sediment.*  
4040 1428  
4041  
4042 1429 *Res.* 74, 453–461. doi:10.1306/112003740453  
4043  
4044 1430 Hawie, N., Deschamps, R., Nader, F.H., Gorini, C., 2013a. Sedimentological and stratigraphic  
4045  
4046 1431 evolution of northern Lebanon since the Late Cretaceous: implications for the Levant  
4047  
4048 1432 margin and basin. doi:10.1007/s12517-013-0914-5  
4049  
4050 1433 Hawie, N., Gorini, C., Deschamps, R., Nader, F.H., Montadert, L., Granjeon, D., Baudin, F.,  
4051  
4052 1434 2013b. Tectono-stratigraphic evolution of the northern Levant Basin (offshore Lebanon).  
4053  
4054 1435 *Mar. Pet. Geol.* 48, 392–410. doi:10.1016/j.marpetgeo.2013.08.004  
4055  
4056 1436 Hernández-Molina F.J, et al., 2014. Onset of Mediterranean outflow into the North Atlantic.  
4057  
4058 1437 *Science* 344, 1244–1250. doi: 10.1126/science.1251306  
4059  
4060 1438 Hilgen, F., Kuiper, K., Krijgsman, W., Snel, E., Laan, E. Van Der, van der Laan, E., 2007.  
4061  
4062 1439 Astronomical tuning as the basis for high resolution chronostratigraphy: The intricate  
4063  
4064 1440 history of the Messinian Salinity Crisis. *Stratigraphy* 4, 231–238.  
4065  
4066 1441 Hilgen, F.J., Bissoli, L., Iaccarino, S., Krijgsman, W., Meijer, R., Negri, A., Villa, G., 2000.  
4067  
4068 1442 Integrated stratigraphy and astrochronology of the Messinian GSSP at Oued Akrech  
4069  
4070 1443 (Atlantic Morocco). *Earth Planet. Sci. Lett.* 182, 237–251. doi:10.1016/S0012-  
4071  
4072 1444 821X(00)00247-8  
4073  
4074 1445 Hilgen, F.J., Krijgsman, W., 1999. Cyclostratigraphy and astrochronology of the Tripoli  
4075  
4076 1446 diatomite formation (pre-evaporite Messinian, Sicily, Italy). *Terra Nov.* 11, 16–22.  
4077  
4078 1447 doi:10.1046/j.1365-3121.1999.00221.x  
4079  
4080 1448 Hilgen, F.J., Krijgsman, W., Langereis, C.G., Lourens, L.J., Santarelli, A., Zachariasse, W.J.,  
4081  
4082  
4083  
4084  
4085  
4086  
4087  
4088

4089  
4090  
4091 1449 1995. Extending the astronomical (polarity) time scale into the Miocene. *Earth Planet. Sci.*  
4092  
4093 1450 *Lett.* 136, 495–510. doi:10.1016/0012-821X(95)00207-S  
4094  
4095  
4096 1451 Hsü, K.J., 1973. The desiccated deep-basin model for the Messinian events, in: Drooger, C.W.  
4097  
4098 1452 (Ed.), *Messinian Events in the Mediterranean*. North-Holland Publ. Co., Amsterdam, pp.  
4099  
4100 1453 60–67.  
4101  
4102 1454 Hsü, K. J., Ryan, W.B.F., Schreiber, B.C., 1973. Petrography of a halite sample from hole 134 -  
4103  
4104 1455 balearic abyssal plain, in: *Initial Reports of the Deep Sea Drilling Project 13, No. Part 2*. pp.  
4105  
4106 1456 708–711.  
4107  
4108  
4109 1457 Hsü, K.J., Montadert, L., Bernoulli, D., Bizon, G., Cita, M., Erickson, A., Fabricius, F., Garrison,  
4110  
4111 1458 R.E., Kidd, R.B., Mélières, F., Müller, C., Wright, R.C., 1978a. Site 374: Messina Abyssal  
4112  
4113 1459 Plain, in: *Initial Reports of the Deep Sea Drilling Project: DSDP Volume XLII Part 1*. p. 43.  
4114  
4115 1460 doi:10.2973/dsdp.proc.42-1.105.1978  
4116  
4117  
4118 1461 Hsü, K.J., Montadert, L., Bernoulli, D., Bizon, G., Cita, M., Erickson, A., Fabricius, F., Garrison,  
4119  
4120 1462 R.E., Kidd, R.B., Mélières, F., Müller, C., Wright, R.C., 1978b. Sites 375 and 376: Florence  
4121  
4122 1463 Rise, in: *Initial Reports of the Deep Sea Drilling Project: DSDP Volume XLII Part 1*. p. 86.  
4123  
4124 1464 Hüsing, S.K., Cascella, A., Hilgen, F.J., Krijgsman, W., Kuiper, K.F., Turco, E., Wilson, D.,  
4125  
4126 1465 2010. Astrochronology of the Mediterranean Langhian between 15 . 29 and 14 . 17 Ma.  
4127  
4128 1466 *Earth Planet. Sci. Lett.* 290, 254–269. doi:10.1016/j.epsl.2009.12.002  
4129  
4130  
4131 1467 Hüsing, S.K., Kuiper, K.F., Link, W., Hilgen, F.J., Krijgsman, W., 2009. The upper Tortonian-  
4132  
4133 1468 lower Messinian at Monte dei Corvi (Northern Apennines, Italy): Completing a  
4134  
4135 1469 Mediterranean reference section for the Tortonian Stage. *Earth Planet. Sci. Lett.* 282, 140–  
4136  
4137 1470 157. doi:10.1016/j.epsl.2009.03.010  
4138  
4139 1471 Karakitsios, V., Cornée, J.J., Tsourou, T., Moissette, P., Kontakiotis, G., Agiadi, K.,

4145  
4146  
4147 1472 Manoutsoglou, E., Triantaphyllou, M., Koskeridou, E., Drinia, H., Roussos, D., 2017.  
4148  
4149 1473 Messinian salinity crisis record under strong freshwater input in marginal, intermediate, and  
4150  
4151 deep environments: The case of the North Aegean. *Palaeogeogr. Palaeoclimatol.*  
4152 1474  
4153 *Palaeoecol.* 485, 316–335. doi:10.1016/j.palaeo.2017.06.023  
4154 1475  
4155  
4156 1476 Keogh, S.M., Butler, R.W.H., 1999. The Mediterranean water body in the late Messinian:  
4157  
4158 interpreting the record from marginal basins on Sicily. *J. Geol. Soc. London.* 156, 837–846.  
4159 1477  
4160 doi:10.1144/gsjgs.156.4.0837  
4161 1478  
4162  
4163 1479 Krijgsman, W., Blanc-Valleron, M.M., Flecker, R., Hilgen, F.J., Kouwenhoven, T.J., Merle, D.,  
4164  
4165 Orszag-Sperber, F., Rouchy, J.M., 2002. The onset of the Messinian salinity crisis in the  
4166 1480  
4167 Eastern Mediterranean (Pissouri Basin, Cyprus). *Earth Planet. Sci. Lett.* 194, 299–310.  
4168 1481  
4169 doi:10.1016/S0012-821X(01)00574-X  
4170 1482  
4171  
4172 1483 Krijgsman, W., Fortuin, A.R., Hilgen, F.J., Sierro, F.J., 2001. Astrochronology for the Messinian  
4173  
4174 Sorbas basin (SE Spain) and orbital (precessional) forcing for evaporite cyclicity. *Sediment.*  
4175  
4176 *Geol.* 140, 43–60. doi:10.1016/S0037-0738(00)00171-8  
4177 1485  
4178 1486 Krijgsman, W., Garces, M., Agusti, J., Raffi, I., Taberner, C., Zachariasse, W.J., 2000. The  
4179  
4180 “Tortonian salinity crisis” of the eastern Betics (Spain). *Earth Planet. Sci. Lett.* 181, 497–  
4181  
4182 511. doi:10.1016/S0012-821X(00)00224-7  
4183 1488  
4184 1489 Krijgsman, W., Hilgen, F.J., Negri, A., Wijbrans, J.R., Zachariasse, W.J., 1997. The Monte del  
4185  
4186 Casino section (Northern Apennines, Italy): A potential Tortonian/Messinian boundary  
4187 1490  
4188 stratotype? *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 133, 27–47. doi:10.1016/S0031-  
4189 1491  
4190 0182(97)00039-4  
4191 1492  
4192  
4193 1493 Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999. Chronology, causes and  
4194  
4195 progression of the Messinian salinity crisis. *Nature* 400, 652–655. doi:10.1038/23231.  
4196 1494  
4197  
4198  
4199  
4200

4201  
4202  
4203 1495 Krijgsman, W., Meijer, P.T., 2008. Depositional environments of the Mediterranean “Lower  
4204  
4205 1496 Evaporites” of the Messinian salinity crisis: Constraints from quantitative analyses. *Mar.*  
4206  
4207  
4208 1497 *Geol.* doi:10.1016/j.margeo.2008.04.010  
4209  
4210 1498 Krijgsman, W., Stoica, M., Vasiliev, I., Popov, V. V., 2010. Rise and fall of the Paratethys Sea  
4211  
4212 1499 during the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.* 290, 183–191.  
4213  
4214 1500 doi:10.1016/j.epsl.2009.12.020.  
4215  
4216 1501 Lange, G.J. De, Krijgsman, W., 2010. Messinian salinity crisis: A novel unifying shallow  
4217  
4218 gypsum / deep dolomite formation mechanism. *Mar. Geol.* 275, 273–277.  
4219 1502  
4220 doi:10.1016/j.margeo.2010.05.003  
4221 1503  
4222  
4223 1504 Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-  
4224  
4225 1505 term numerical solution for the insolation quantities of the Earth. *Astron. As-trophys.*  
4226  
4227 1506 *Astron. Astrophys.* 428, 261–285. doi:10.1051/0004-6361:20041335  
4228  
4229 1507 Leila, M., Kora, M.A., Ahmed, M.A., Ghanem, A., 2016. Sedimentology and reservoir  
4230  
4231 1508 characterization of the Upper Miocene Qawasim Formation, El-Tamad Oil Field onshore  
4232  
4233 Nile Delta, Egypt. *Arab. J. Geosci.* 9, 1–13. doi:10.1007/s12517-015-2088-9  
4234 1509  
4235  
4236 1510 Lofi, J., Camerlenghi, A., 2014. Messinian Salinity Crisis - DREAM (Deep-sea Record of  
4237  
4238 1511 Mediterranean Messinian events) drilling projects Messinian Salinity Crisis - DREAM  
4239  
4240 1512 (Deep-sea Record of Mediterranean Messinian events) drilling projects, in: EGU. Vienna, p.  
4241  
4242 1513 1.  
4243  
4244 1514 Lofi, J., Sage, F., Deverchere, J., Loncke, L., Maillard, A., Gaullier, V., Thion, I., Gillet, H.,  
4245  
4246 1515 Guennoc, P., Gorini, C., 2011. Refining our knowledge of the Messinian salinity crisis  
4247  
4248 1516 records in the offshore domain through multi-site seismic analysis. *Bull. la Soc. Geol. Fr.*  
4249  
4250 1517 182, 163–180. doi:10.2113/gssgfbull.182.2.163  
4251  
4252  
4253  
4254  
4255  
4256

4257  
4258  
4259 1518 Lohmann, J., Ditlevsen, P.D., 2018. Random and externally controlled occurrences of  
4260  
4261 1519 Dansgaard-Oeschger events. *Clim. Past* 14, 609–617. doi:10.5194/cp-14-609-2018  
4262  
4263  
4264 1520 Lugli, S., Gennari, R., Gvirtzman, Z., Manzi, V., Roveri, M., Schreiber, B.C., 2013. Evidence of  
4265  
4266 1521 clastic evaporites in the canyons of the Levant Basin (Israel): implications for the Messinian  
4267  
4268 1522 Salinity Crisis. *J. Sediment. Res.* 83, 942–954. doi:10.2110/jsr.2013.72  
4269  
4270 1523 Lugli, S., Manzi, V., Roveri, M., Schreiber, B.C., 2015. The deep record of the Messinian  
4271  
4272 1524 salinity crisis: Evidence of a non-desiccated Mediterranean Sea. *Palaeogeogr.*  
4273  
4274 1525 *Palaeoclimatol. Palaeoecol.* 433, 201–218. doi:10.1016/j.palaeo.2015.05.017  
4275  
4276 1526 Lugli, S., Schreiber, B.C., Triberti, B., 1999. Giant polygons in the Realmonte Mine (Agrigento,  
4277  
4278 1527 Sicily); evidence for the desiccation of a Messinian halite basin. *J. Sediment. Res.* 69, 764–  
4279  
4280  
4281 1528 771. doi:10.2110/jsr.69.764  
4282  
4283 1529 McArthur, J. M., Howarth, R. J., Shield, G. A., 2012. Chapter 7: Strontium Isotope Stratigraphy.  
4284  
4285 1530 In *The Geologic Time Scale*, eds. F. M. Gredstein, J. G. Ogg, M. D. Schmotz & G. M. Ogg,  
4286  
4287 1531 1144 Elsevier.  
4288  
4289 1532 Madof, A.S., Bertoni, C., Lofi, J., 2019. Discovery of vast fluvial deposits provides evidence for  
4290  
4291 1533 drawdown during the late Miocene Messinian salinity crisis. *Geology* 47, 171–174.  
4292  
4293 1534 doi:10.1130/G45873.1  
4294  
4295 1535 Manzi, V., Gennari, R., Hilgen, F., Krijgsman, W., Lugli, S., 2013. Age refinement of the  
4296  
4297 1536 Messinian salinity crisis onset in the Mediterranean. doi:10.1111/ter.12038  
4298  
4299  
4300 1537 Manzi, V., Gennari, R., Lugli, S., Persico, D., Reghizzi, M., Roveri, M., Schreiber, B.C., Calvo,  
4301  
4302 1538 R., Gavrieli, I., Gvirtzman, Z., 2018. The onset of the Messinian salinity crisis in the deep  
4303  
4304 1539 Eastern Mediterranean basin. *Terra Nov.* 38, 42–49. doi:10.1111/ter.12325  
4305  
4306 1540 Manzi, V., Gennari, R., Lugli, S., Roveri, M., Scafetta, N., Charlotte, B., 2012. High-frequency  
4307  
4308  
4309  
4310  
4311  
4312

4313  
4314  
4315 1541 cyclicity in the Mediterranean Messinian evaporites: evidence for solar-lunar climate  
4316  
4317 1542 forcing. *J. Sediment. Res.* 82, 991–1005. doi:10.2110/jsr.2012.81  
4318  
4319  
4320 1543 Manzi, V., Lugli, S., Roveri, M., Dela Pierre, F., Gennari, R., Lozar, F., Natalicchio, M.,  
4321  
4322 1544 Schreiber, B.C., Taviani, M., Turco, E., 2015. The Messinian salinity crisis in Cyprus: A  
4323  
4324 1545 further step towards a new stratigraphic framework for Eastern Mediterranean. *Basin Res.*  
4325  
4326 1546 28, 207–236. doi:10.1111/bre.12107  
4327  
4328 1547 Manzi, V., Lugli, S., Roveri, M., Schreiber, B.C., 2009. A new facies model for the Upper  
4329  
4330 1548 Gypsum of Sicily (Italy): Chronological and palaeoenvironmental constraints for the  
4331  
4332 1549 Messinian salinity crisis in the Mediterranean. *Sedimentology* 56, 1937–1960.  
4333  
4334 1550 doi:10.1111/j.1365-3091.2009.01063.x  
4335  
4336  
4337 1551 Manzi, V., Lugli, S., Roveri, M., Schreiber, B.C., Gennari, R., 2011. The Messinian “Calcare di  
4338  
4339 1552 Base” (Sicily, Italy) revisited. *Bull. Geol. Soc. Am.* 123, 347–370. doi:10.1130/B30262.1  
4340  
4341 1553 Marzocchi, A., Lunt, D.J., Flecker, R., Bradshaw, C.D., Farnsworth, A., Hilgen, F.J., 2015.  
4342  
4343 1554 Orbital control on late Miocene climate and the North African monsoon: Insight from an  
4344  
4345 1555 ensemble of sub-precessional simulations. *Clim. Past* 11, 1271–1295. doi:10.5194/cp-11-  
4346  
4347 1556 1271-2015  
4348  
4349 1557 Meilijson, A., Ashckenazi-Polivoda, S., Ron-Yankovich, L., Illner, P., Alsenz, H., Speijer, R.P.,  
4350  
4351 1558 Almogi-Labin, A., Feinstein, S., Berner, Z., Püttmann, W., Abramovich, S., 2014.  
4352  
4353 1559 Chronostratigraphy of the Upper Cretaceous high productivity sequence of the southern  
4354  
4355 1560 Tethys, Israel. *Cretac. Res.* 50. doi:10.1016/j.cretres.2014.04.006  
4356  
4357  
4358 1561 Meilijson, A., Steinberg, J., Hilgen, F., Bialik, O.M., Waldmann, N.D., Makovsky, Y., 2018.  
4359  
4360 1562 Deep-basin evidence resolves a 50-year-old debate and demonstrates synchronous onset of  
4361  
4362 1563 Messinian evaporite deposition in a non-desiccated Mediterranean. *Geology* 46, 4–7.  
4363  
4364  
4365  
4366  
4367  
4368



4369  
4370  
4371 1564 Müller, D.W., Mueller, P.A., 1991. Origin and age of the Mediterranean Messinian evaporites:  
4372  
4373 1565 implications from Sr isotopes. *Earth Planet. Sci. Lett.* doi:10.1016/0012-821X(91)90039-K  
4374  
4375  
4376 1566 Nam, M., Görür, N., Flecker, R., Sak, M., Tüno, C., Ellam, R., Krijgsman, W., Vincent, S.,  
4377  
4378 1567 Dikba, A., 2006. Paratethyan–Mediterranean connectivity in the Sea of Marmara region  
4379  
4380 1568 (NW Turkey) during the Messinian. *Sediment. geo* 188–189, 171–187.  
4381  
4382 1569 doi:10.1016/j.sedgeo.2006.03.004  
4383  
4384 1570 Netzeband, G.L., Hübscher, C.P., Gajewski, D., 2006. The structural evolution of the Messinian  
4385  
4386 1571 evaporites in the Levantine Basin. *Mar. Geol.* 230, 249–273.  
4387  
4388 1572 doi:10.1016/j.margeo.2006.05.004  
4389  
4390 1573 Ochoa, D., Sierro, F.J., Lofi, J., Maillard, A., Flores, J.A., Suarez, M., 2015. Synchronous onset  
4391  
4392 1574 of the Messinian evaporite precipitation: First Mediterranean offshore evidence. *Earth*  
4393  
4394 1575 *Planet. Sci. Lett.* 427, 112–124. doi:10.1016/j.epsl.2015.06.059  
4395  
4396 1576 Ogniben, L., 1957. Petrografia della Serie Solfifera Siciliana e considerazioni geologiche  
4397  
4398 1577 relative. *Memorie Descrittive della Carta Geologica d'Italia* 33, 1–275.  
4399  
4400 1578 Ohneiser, C., Florindo, F., Stocchi, P., Roberts, A.P., DeConto, R.M., Pollard, D., 2015.  
4401  
4402 1579 Antarctic glacio-eustatic contributions to late Miocene Mediterranean desiccation and  
4403  
4404 1580 reflooding. *Nat. Commun.* 6, 8765. doi:10.1038/ncomms9765  
4405  
4406 1581 Peters, K.E., A.E. Kontorovich, J.M.M., 1993. Geochemistry of selected oils and rocks from the  
4407  
4408 1582 central portion of the west Siberian Basin, Russia. *Am. Assoc. Pet. Geol. Bull.* 77, 87–863.  
4409  
4410 1583 Peters, K.E., 1986. Guidelines for Evaluating Petroleum Source Rock Using Programmed  
4411  
4412 1584 Pyrolysis. *Am. Assoc. Pet. Geol. Bull.* 70, 318–329. doi:10.1306/94885688-1704-11D7-  
4413  
4414 1585 8645000102C1865D  
4415  
4416 1586 Peters, K.E., Rohrback, B.G., Kaplan, I.R., 1980. Laboratory-simulated thermal maturation of  
4417  
4418  
4419  
4420  
4421  
4422  
4423  
4424

4425  
4426  
4427 1587 Recent sediments. *Phys. Chem. Earth* 12, 547–557. doi:10.1016/0079-1946(79)90136-8  
4428  
4429 1588 Peters, K.E., Walters Clifford C, Moldowan, J.M., 2005. *The Biomarker Guide, Biomarkers and*  
4430  
4431 *Isotopes in Petroleum Exploration and Earth History, Volume 2.* Cambridge.  
4432 1589  
4433 doi:10.1017/s0016756806212056  
4434 1590  
4435  
4436 1591 Rashid, H., Grosjean, E., 2006. Detecting the source of Heinrich layers: An organic geochemical  
4437  
4438 1592 study. *Paleoceanography* 21. doi:10.1029/2005PA001240  
4439  
4440 1593 Reiche, S., Hübscher, C., Beitz, M., 2014. Fault-controlled evaporite deformation in the Levant  
4441  
4442 1594 Basin, Eastern Mediterranean. *Mar. Geol.* 354, 53–68. doi:10.1016/j.margeo.2014.05.002  
4443  
4444 1595 Richter-Bernburg, G., 1996. *Zechstein-Anhydrite: Fazies und Genese, Geologisches Jahrbuch.*  
4445  
4446 1596 Reihe A, Allgemeine und regionale Geologie Bundesrepublik Deutschland und  
4447  
4448 1597 Nachbargebiete, Tektonik, Stratigraphie, Paläontologie. Bundesanstalt für  
4449  
4450 1598 Geowissenschaften und Rohstoffe.  
4451  
4452 1599 Roberts, G., Peace, D., 2007. Hydrocarbon plays and prospectivity of the Levantine basin,  
4453  
4454 1600 offshore Lebanon and Syria from modern seismic data. *GeoArabia* 12, 99–124.  
4455  
4456 1601 Rouchy, J.M., Caruso, A., 2006. The Messinian salinity crisis in the Mediterranean basin : A  
4457  
4458 1602 reassessment of the data and an integrated scenario. *Sediment. Geol.* 188–189, 35–67.  
4459  
4460 1603 doi:10.1016/j.sedgeo.2006.02.005  
4461  
4462 1604 Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V., Sierro, F.J., Bertini, A.,  
4463  
4464 1605 Camerlenghi, A., De Lange, G., Govers, R., Hilgen, F.J., Hübscher, C., Meijer, P.T., Stoica,  
4465  
4466 1606 M., 2014a. The Messinian Salinity Crisis: Past and future of a great challenge for marine  
4467  
4468 1607 sciences. *Mar. Geol.* 352, 25–58. doi:10.1016/j.margeo.2014.02.002  
4469  
4470 1608 Roveri, M., Gennari, R., Ligi, M., Lugli, S., Manzi, V., Reghizzi, M., 2019. The synthetic  
4471  
4472 1609 seismic expression of the Messinian salinity crisis from onshore records: implications for  
4473  
4474  
4475  
4476  
4477  
4478  
4479  
4480

4481  
4482  
4483 1610 shallow- to deep-water correlations. *Basin Res.* doi:10.1111/bre.12361  
4484  
4485  
4486 1611 Roveri, M., Lugli, S., Manzi, V., Gennari, R., Schreiber, B.C., 2014b. High-resolution strontium  
4487  
4488 1612 isotope stratigraphy of the messinian deep Mediterranean basins: Implications for marginal  
4489  
4490 1613 to central basins correlation. *Mar. Geol.* 349, 113–125. doi:10.1016/j.margeo.2014.01.002  
4491  
4492 1614 Roveri, M., Manzi, V., Bergamasco, A., Falcieri, F.M., Gennari, R., Lugli, S., Schreiber, B.C.,  
4493  
4494 1615 2014c. Dense shelf water cascading and messinian canyons: A new scenario for the  
4495  
4496 1616 mediterranean salinity crisis. *Am. J. Sci.* 314, 751–784. doi:10.2475/05.2014.03  
4497  
4498  
4499 1617 Rullkötter, J., R.M., 1988. Natural and artificial maturation of biological markers in a Toarcian  
4500  
4501 1618 shale from northern Germany, in: Novelli, L.M. and L. (Ed.), *Advances in Organic*  
4502  
4503 1619 *Geochemistry* 1987. Oxford Pergamon Press, pp. 639–645.  
4504  
4505 1620 Ryan, W.B.F., 2011. Geodynamic responses to a two-step model of the Messinian salinity crisis.  
4506  
4507 1621 *Bull. la Soc. Geol. Fr.* 182, 73–78. doi:10.2113/gssgfbull.182.2.73  
4508  
4509 1622 Ryan, W.B.F., 2008. Modeling the magnitude and timing of evaporative drawdown during the  
4510  
4511 1623 Messinian salinity crisis. *Stratigraphy* 5, 227–243.  
4512  
4513 1624 Ryan, W.B.F., 1978. Messinian badlands on the southeastern margin of the Mediterranean Sea.  
4514  
4515 1625 *Mar. Geol.* 27, 349–363. doi:10.1016/0025-3227(78)90039-7  
4516  
4517  
4518 1626 Ryan, W.B.F., 1976. Quantitative evaluation of the depth of the western Mediterranean before,  
4519  
4520 1627 during and after the late Miocene salinity crisis. *Sedimentology* 23, 791–813.  
4521  
4522  
4523 1628 Ryan, W.B.F., 1973. Geodynamic implications of the Messinian crisis of salinity, in: Drooger,  
4524  
4525 1629 D.W. (Ed.), *Messinian Events in the Mediterranean*. Elsevier, Amsterdam, pp. 26–38.  
4526  
4527 1630 Ryan, W.B.F., Cita, M.B., 1978. The nature and distribution of Messinian erosional surfaces -  
4528  
4529 1631 Indicators of a several-kilometer-deep Mediterranean in the Miocene. *Mar. Geol.*  
4530  
4531 1632 doi:10.1016/0025-3227(78)90032-4  
4532  
4533  
4534  
4535  
4536

4537  
4538  
4539 1633 Ryan, W.B.F., Hsü, K.J., Cita, M.B., Dumitrica, P., Lort, J., Maync, W., Nesteroff, W.D., Pautot,  
4540  
4541 G., Stradner, H., 2007. DSDP Volume XIII: 6. Balearic Rise - Site 124. The Shipboard  
4542 1634  
4543 Scientific Party. doi:10.2973/dsdp.proc.13.1973  
4544 1635  
4545  
4546 1636 Ryan, W.B.F., Stanley, D.J., Hersey, J.B., Fahlquist, D.A., Allan, T.D., 1971. The tectonics and  
4547  
4548 geology of the Mediterranean Sea. In: Maxwell, A.E. (Ed.), *The Sea*. Wiley- Interscience,  
4549 1637  
4550 New York, pp. 387–492.  
4551 1638  
4552  
4553 1639 Scafetta, N., Milani, F., Bianchini, A., Ortolani, S., 2016. On the astronomical origin of the  
4554  
4555 Hallstatt oscillation found in radiocarbon and climate records throughout the Holocene.  
4556 1640  
4557 Earth-Science Rev. 162, 24–43. doi:10.1016/j.earscirev.2016.09.004  
4558 1641  
4559 1642 Scalán, E.S., Smith, J.E., 1970. An improved measure of the odd-even predominance in the  
4560  
4561 normal alkanes of sediment extracts and petroleum. *Geochim. Cosmochim. Acta* 34, 611–  
4562 1643  
4563 620. doi:10.1016/0016-7037(70)90019-0  
4564 1644  
4565 1645 Schmalz, R.F., 1969. Deep-Water Evaporite Deposition: A Genetic Model. *Am. Assoc. Pet.*  
4566  
4567 *Geol. Bull.* 53, 798–823. doi:10.1306/5D25C7FD-16C1-11D7-8645000102C1865D  
4568 1646  
4569  
4570 1647 Schulz, M., 2002. On the 1470-year pacing of Dansgaard-Oeschger warm events.  
4571  
4572 *Paleoceanography* 17, 4-1-4–9. doi:10.1029/2000PA000571  
4573 1648  
4574 1649 Schulz, M., Mudelsee, M., 2002. REDFIT: Estimating red-noise spectra directly from unevenly  
4575  
4576 spaced paleoclimatic time series. *Comput. Geosci.* 28, 421–426. doi:10.1016/S0098-  
4577 1650  
4578 3004(01)00044-9  
4579 1651  
4580 1652 Selli, R., 1954. Il Bacino del Metauro. *Giornale di Geologia* 24, 1–294.  
4581  
4582  
4583 1653 Sepúlveda, J., Wendler, J.E., Summons, R.E., Hinrichs, K.U., 2009. Rapid Resurgence of Marine  
4584  
4585 Productivity After the Cretaceous-Paleogene Mass Extinction. *Science* (80-. ). 326, 129–  
4586 1654  
4587 132.  
4588 1655  
4589  
4590  
4591  
4592

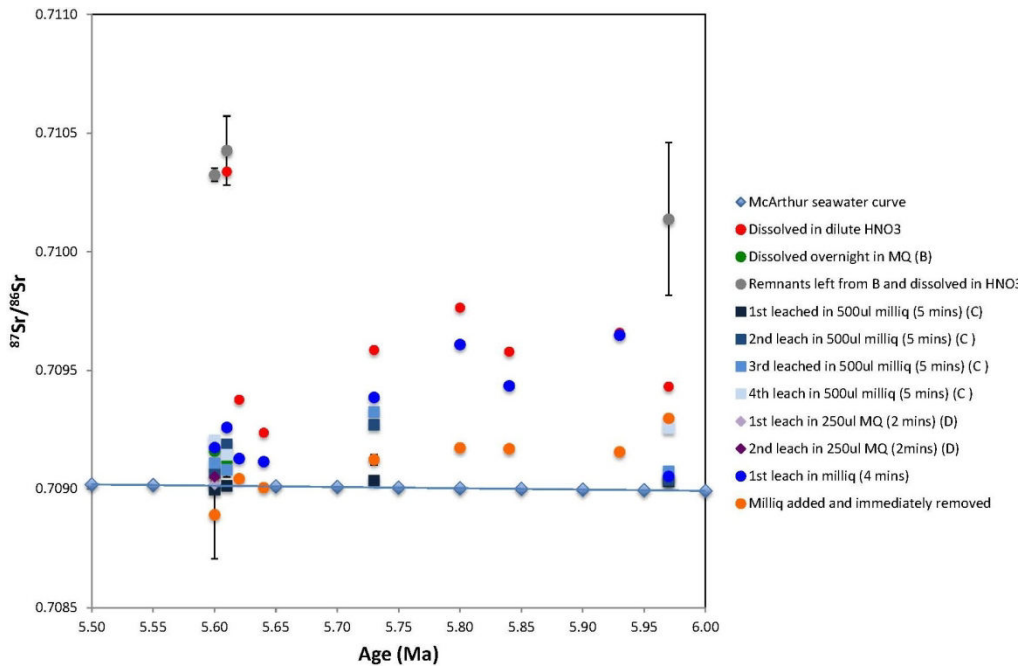
4593  
4594  
4595 1656 Sierro, F.J., Hilgen, F.J., Krijgsman, W., Flores, J.A., 2001. The Abad composite (SE Spain): A  
4596  
4597 1657 Messinian reference section for the Mediterranean and the APTS. *Palaeogeogr.*  
4598  
4599  
4600 1658 *Palaeoclimatol. Palaeoecol.* 168, 141–169. doi:10.1016/S0031-0182(00)00253-4  
4601  
4602 1659 Simon, D., Marzocchi, A., Flecker, R., Lunt, D.J., Hilgen, F.J., Meijer, P.T., 2017. Quantifying  
4603  
4604 1660 the Mediterranean freshwater budget throughout the late Miocene: New implications for  
4605  
4606 1661 sapropel formation and the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.* 472, 25–37.  
4607  
4608 1662 doi:10.1016/j.epsl.2017.05.013  
4609  
4610 1663 Simon, D., Meijer, P.T., 2017. Salinity stratification of the Mediterranean Sea during the  
4611  
4612 1664 Messinian crisis: A first model analysis. *Earth Planet. Sci. Lett.* 479, 366–376.  
4613  
4614 1665 doi:10.1016/j.epsl.2017.09.045  
4615  
4616 1666 Sirota, I., Ali, A., Lensky, N.G., 2016. Seasonal variations of halite saturation in the Dead Sea.  
4617  
4618 1667 *Water Resour. Res.* 52. doi:10.1002/2014WR016618  
4619  
4620  
4621 1668 Sirota, I., Enzel, Y., Lensky, N.G., 2017. Temperature seasonality control on modern halite  
4622  
4623 1669 layers in the Dead Sea: In situ observations. *Bull. Geol. Soc. Am.* 129, 1181–1194.  
4624  
4625 1670 doi:10.1130/B31661.1  
4626  
4627 1671 Sonnenfeld, P., Finetti, I., 2011. Messinian Evaporites in the Mediterranean: A Model of  
4628  
4629 1672 Continuous Inflow and Outflow, in: *Geological Evolution of the Mediterranean Basin.*  
4630  
4631 1673 doi:10.1007/978-1-4613-8572-1-17  
4632  
4633  
4634 1674 Sonnenfeld, P., Hudec, P.P., 1983. Clay laminations in Halite: Their Cause and Effect, in: *Sixth*  
4635  
4636 1675 *International Symposium on Salt.* pp. 51–56.  
4637  
4638 1676 Steinberg, J., Gvirtzman, Z., Folkman, Y., 2010. New age constraints on the evolution of the Mt  
4639  
4640 1677 Carmel structure and its implications on a Late Miocene extensional phase of the Levant  
4641  
4642 1678 continental margin. *J. Geol. Soc. London.* 167, 203–216. doi:10.1144/0016-76492009-089  
4643  
4644  
4645  
4646  
4647  
4648

4649  
4650  
4651 1679 Steinberg, J., Gvirtzman, Z., Folkman, Y., Garfunkel, Z., 2011. Origin and nature of the rapid  
4652  
4653 1680 late Tertiary filling of the Levant Basin. *Geology* 39, 355–358. doi:10.1130/G31615.1  
4654  
4655  
4656 1681 Steinhilber, F., Abreu, J.A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkila, U., Kubik,  
4657  
4658 1682 P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H., Wilhelms, F.,  
4659  
4660 1683 2012. 9,400 Years of Cosmic Radiation and Solar Activity From Ice Cores and Tree Rings.  
4661  
4662 1684 *Proc. Natl. Acad. Sci.* 109, 5967–5971. doi:10.1073/pnas.1118965109  
4663  
4664 1685 Steinhorn, I., 1983. In situ salt precipitation at the Dead Sea. *Limnol. Oceanogr.* 28, 580–583.  
4665  
4666 1686 doi:10.4319/lo.1983.28.3.0580  
4667  
4668 1687 Stiller, M., Gat, J.R., Kaushansky, P., 1997. Halite Precipitation and Sediment Deposition As  
4669  
4670 1688 Measured in Sediment Traps Deployed in the Dead Sea: 1981-1983. *Dead Sea lake its*  
4671  
4672 1689 *settings* 161–170.  
4673  
4674  
4675 1690 Stoica, M., Krijgsman, W., Fortuin, A., Gliozzi, E., 2016. Paratethyan ostracods in the Spanish  
4676  
4677 1691 Lago-Mare: More evidence for interbasinal exchange at high Mediterranean sea level.  
4678  
4679 1692 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 441, 854–870. doi:10.1016/j.palaeo.2015.10.034  
4680  
4681 1693 ten Haven, H.L., de Leeuw, J.W., Schenck, P.A., 1985. Organic geochemical studies of a  
4682  
4683 1694 Messinian evaporitic basin, northern Apennines (Italy) I: Hydrocarbon biological markers  
4684  
4685 1695 for a hypersaline environment. *Geochim. Cosmochim. Acta* 49, 2181–2191.  
4686  
4687 1696 Tomas, C.R., 1996. *Identifying Marine Phytoplankton*, Academic Press Inc. San Diego.  
4688  
4689 1697 doi:10.1016/S0025-3227(97)81154-1  
4690  
4691  
4692 1698 Topper, R. P. M., Flecker, R., Meijer, P., Wortel, M. J. R., 2011. A box model of the Late  
4693  
4694 1699 Miocene Mediterranean Sea: implications from combined <sup>87</sup>Sr/<sup>86</sup>Sr and salinity data.  
4695  
4696 1700 *Paleoceanography*, 26.  
4697  
4698 1701 Topper, R.P.M., Lugli, S., Manzi, V., Roveri, M., Meijer, P.T., 2014. Precessional control of Sr  
4699  
4700  
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4702  
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4705  
4706  
4707 1702 ratios in marginal basins during the Messinian Salinity Crisis? *Geochemistry, Geophys.*  
4708  
4709 *Geosystems* 15, 1926–1944. doi:10.1002/2013GC005192  
4710 1703  
4711  
4712 1704 van den Berg, B.C.J., Sierro, F.J., Hilgen, F.J., Flecker, R., Larrasoña, J.C., Krijgsman, W.,  
4713  
4714 1705 Flores, J.A., Mata, M.P., Bellido Martín, E., Civis, J., González-Delgado, J.A., 2015.  
4715  
4716 1706 Astronomical tuning for the upper Messinian Spanish Atlantic margin: Disentangling basin  
4717  
4718 1707 evolution, climate cyclicity and MOW. *Glob. Planet. Change* 135, 89–103.  
4719  
4720 1708 doi:10.1016/j.gloplacha.2015.10.009  
4721  
4722 1709 Vasiliev, I., Mezger, E.M., Lugli, S., Reichart, G., Manzi, V., Roveri, M., 2017. How dry was the  
4723  
4724 1710 Mediterranean during the Messinian salinity crisis ? *Palaeogeogr. Palaeoclimatol.*  
4725  
4726 1711 *Palaeoecol.* 471, 120–133. doi:10.1016/j.palaeo.2017.01.032  
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1713 **Supplementary Figures**



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*Figure S1. Strontium stable isotope analysis*

Results obtained by the different protocols used for strontium stable isotope analysis with respect to the McArthur et al. (2012) seawater curve. Note the large discrepancies between the results obtained by the different methods used, indicating a highly probable contamination from the drilling mud used during the retrieval of the halite cuttings samples.



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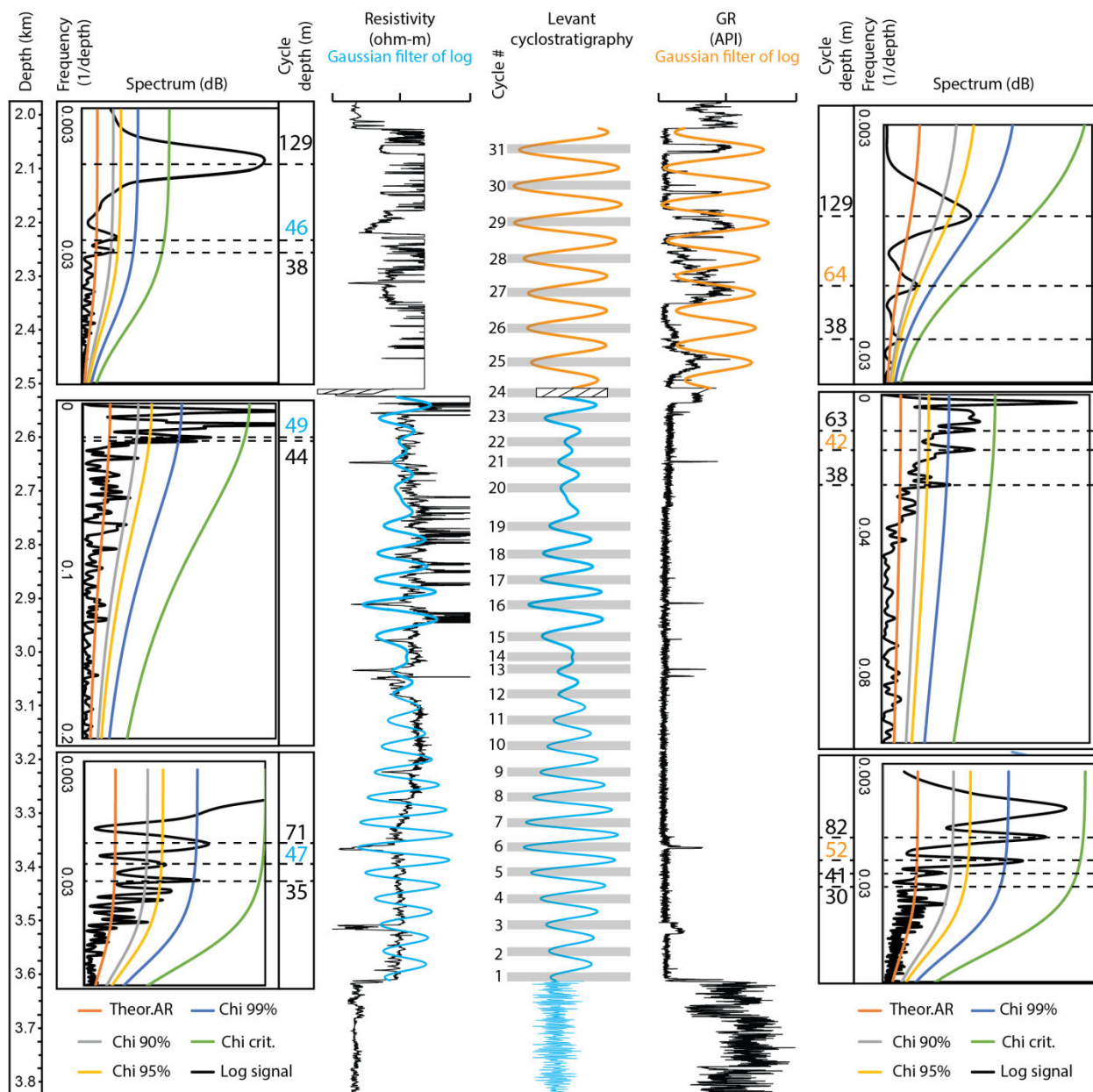


Figure S2. Spectral analysis of the Dolphin well-log curves.

Data shown are the spectral analysis of the resistivity (blue, left) and gamma ray (orange, right) well log curves using REDFIT spectral analysis procedure in Matlab, PAST and Analyseries software. Each log is bounded by respective REDFIT (left of resistivity and right of gamma ray logs) and the combined optimal cyclostratigraphy (center). The REDFIT procedure fits the time series to a red noise model null hypothesis (Theor. AR), produces 'false-alarm' parametric

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1730 approximations (chi<sup>2</sup> of 90%, 95%, and 99%) and a 'critical false-alarm' level (chi crit.). REDFIT  
1731 analyses were run by intervals, defined according to the logs expression as follows: from the  
1732 base to 3175 m, from 3175 to 2560 m, and from 2560 m to the top of the evaporitic bed.

Sample depth (m)	Depositional units, Dolphin-1, Levant Basin	<i>n</i> -alkane distribution					
		ng SCA/g rock	ng LCA/g rock	LCA/SCA	ACL	CPI	Pr/Ph
2655	Interbedded Evaporites	5.3	8.3	1.6	25	2.9	0.6
2709		9.9	17.0	1.7	25	1.9	0.1
3402	Argillaceous Diatomites	15.9	32.3	2.1	25	4.1	0.9
3474		29.2	52.2	1.8	25	12.3	1.1
3675	Pre-Evaporites	16.4	26.9	1.6	25	5.8	1.0
3810		7.5	5.5	0.7	23	7.4	1.1

**Table 1. Indices and distribution of *n*-alkanes as measured from the aliphatic hydrocarbons, Levant Basin MSC lipid extract.** Depositional units are described in the text and presented in Figs- 2 and 3. SCA – short chain alkanes (C<sub>15-21</sub>), LCA – long chain alkanes (C<sub>27-35</sub>), ACL – average chain length, CPI – carbon preference index (Bray and Evans, 1961), expressed as the following relation (*sensu* Vasiliev et al., 2017):  $CPI = (((N_{25} + N_{27} + N_{29} + N_{31} + N_{33}) / (N_{24} + N_{26} + N_{28} + N_{30} + N_{32})) + ((N_{25} + N_{27} + N_{29} + N_{31} + N_{33}) / (N_{26} + N_{28} + N_{30} + N_{32} + N_{34}))) * 0.5$ , where N represents the relative abundance for individual *n*-alkanes. Pr/Ph is the ratio between the pristane and phytane measured from the extracts.

Sample depth (m)	Depositional units, Dolphin-1, Levant Basin	Steranes				Hopanes		
		C <sub>27</sub>		C <sub>28</sub>		C <sub>30</sub>	C <sub>31</sub>	
		C <sub>27</sub> ααα20S/ C <sub>27</sub> ααα20R	Amount of rearranged steranes	C <sub>28</sub> αββ20S/ C <sub>28</sub> αββ20R	C <sub>28</sub> ααα 20S/ C <sub>28</sub> ααα 20R	C <sub>30</sub> βα/ C <sub>30</sub> αβ	C <sub>31</sub> αβS/ C <sub>31</sub> αβR	C <sub>31</sub> βα/ C <sub>31</sub> ββ
2655	Interbedded Evaporites	0.74	High	1.37	0.43	0.02	1.19	0.64
2709		0.82	High	1.39	0.50	0.07	1.15	0.39
3402	Argillaceous Diatomites	0.26	Low	0.01	0.04	1.16	0.07	0.16
3474		0.29	Low	0.03	0.08	1.40	0.03	0.10
3675	Pre-Evaporites	1.66	Moderate	0.06	0.28	0.32	0.79	0.16
3810		0.72	Moderate	1.14	0.43	0.22	0.73	0.02

**Table 2. Indices and distribution of steranes and hopanes measured by selective reaction monitoring (SRM) of the aliphatic hydrocarbons, Levant Basin MSC lipid extract.** Depositional units as in Table 1. Selected samples and thermal maturity-dependent ratios from SRM analysis include C<sub>27</sub> steranes (Ensminger et al., 1978; Peters et al., 2005, 1980), and C<sub>30</sub> and C<sub>31</sub> hopanes (Peters and Moldowan, 1993; Rullkötter and Marzi, 1988). Note the higher maturity values in the Interbedded Evaporites relative to the over- and underlying intervals.

Sample depth (m)	Depositional units, Dolphin-1, Levant Basin	<i>n</i> -alkane distribution					
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		C <sub>27</sub> ααα20S/ C <sub>27</sub> ααα20R	Amount of rearranged steranes	C <sub>28</sub> αββ20S/ C <sub>28</sub> αββ20R	C <sub>28</sub> ααα 20S/ C <sub>28</sub> ααα 20R	C <sub>30</sub> βα/ C <sub>30</sub> αβ	C <sub>31</sub> αβS/ C <sub>31</sub> αβR	C <sub>31</sub> βα/ C <sub>31</sub> ββ
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