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Over half a century of Messinian salinity crisis

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ABSTRACT

Did the Mediterranean ever become a desert during Messinian or was it a huge hyperhaline water body? According to Selli, the introduction of the concept and name of the Messinian Salinity Crisis in 1954, the second hypothesis was correct, but he did not succeed in preventing the rapid growth of popularity of the first hypothesis, triggered by the DSD Mediterranean campaign during the 1970s. The ensuing desiccation theory became popular enough to be included in elementary text books.

The controversy has been revived in the new millennium and much former proof of the theory is now in doubt. The Mediterranean was not totally isolated, but often supplied with normal marine water. Instead of km-deep drawdown, shallower-to-absent level drop is favoured. Exposed canyons at the mouth of major Mediterranean rivers have turned into submarine channels filled by clastic sulphates. The mega-catastrophic potential of the desiccation theory has turned out to be less worrying. Perhaps the text books of our grandchildren should be updated.

Within the frame of new evidence regarding normal water supply, even from the Indian Ocean, are discussed, based on two new palinspastic Messinian maps. However, reduced sharpness in the controversy and increasing consensus reached among specialists depend on ongoing inferred correlations between on-land and deep-marine Messinian evaporites. Only drilling across the whole, deep Mediterranean evaporite sequences can back-up the reliability of the correlation and validity of these new views.

Key words: biotas, controversy, desiccation, hypersalinity, palaeogeography

Más de medio siglo de crisis de salinidad Mesiniense

RESUMEN

¿Fue el Mediterráneo alguna vez durante el Mesiniense un desierto, o fue una enorme masa de agua hipersalina? Para Selli, que introdujo el nombre de Crisis de Salinidad del Mesiniense en 1954, la segunda alternativa era la correcta, pero no pudo impedir el rápido crecimiento de la primera opción tras la campaña de sondeos profundos en el Mediterráneo realizada en los 70. La resultante teoría de la desecación se hizo tan popular que llegó hasta los libros de texto de la enseñanza elemental.

La controversia se ha revivido en el nuevo milenio y muchas pruebas previas de la teoría están ahora en duda. El Mediterráneo no estaba completamente aislado, sino que a menudo recibía aguas marinas normales. Son más frecuentes descensos poco profundos o nulos frente a descensos de kilómetros de profundidad. Los cañones en las bocas de los principales ríos mediterráneos se han convertido en canales submarinos colmatados por sulfatos clásticos. El potencial mega-catastrófico de la teoría de la desecación se ha vuelto menos preocupante. Quizás se deberían actualizar los libros de texto de nuestros nietos.

En este marco, se discuten nuevas evidencias del aporte de aguas normales también para el caso del Océano Índico, en base a nuevos mapas palinspáticos del Mesiniense. Sin embargo la reducción de aristas en la controversia y el aumento del consenso entre los especialistas, depende de las correlaciones inferidas y en curso, entre las evaporitas mesinienses continentales y las marinas profundas. Solo sondeos que atravesasen todas las secuencias evaporíticas profundas del Mediterráneo, podrían respaldar la fiabilidad de la correlación y validez de estos nuevos puntos de vista.

Palabras clave: biotas, controversia, desecación, hipersalinidad, paleogeografía

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

La Crisis de Salinidad del Mesiniense (CSM) denominada así por Selli (1960, 1964) pero que ya había introducida anteriormente (Selli 1954), es más antigua que la controversia sobre su interpretación. Los debates empezaron en 1973 con el Proyecto de Perforación Marina Profunda (Deep Sea Drilling Projec. DSDP) en el Mediterráneo, como discrepancias entre geólogos y geofísicos/geólogos marinos. El cruel debate que siguió también se polarizó. Más tarde los términos de la controversia se suavizaron y se ha alcanzado un consenso (diverso).

Un Mediterráneo completamente desecado ha perdido apoyos. El aislamiento total del Mediterráneo se ha sustituido hoy en día por el aumento del aporte de aguas marinas normales, con sus faunas y floras. El escenario ha pasado de la desecación a la influencia marina normal en una masa de agua hipersalina. Selli en realidad ha centrado el parámetro básico, la salinidad de este gigante salino, que está llevando gradualmente a diferentes autores y modelos a un consenso. Selli (1973) estaba también pensando a largo plazo cuando predijo "ambos modelos, incluso en la misma zona o cuenca, se podrían justificar". Un descenso importante y kilométrico del Mediterráneo compite ahora con descensos más someros en un orden de magnitud o incluso ausentes de la cuenca, reviviendo opiniones anteriores.

El modelo de desecación profunda, aunque todavía tiene su atractivo, ha perdido la mayor parte de su potencial catastrófico. Cuando se observa que los cañones levantinos marginales están rellenos con facies de sulfatos clásticos resultado de deslizamientos subacuáticos (en lugar de depósitos sub-aéreos tipo sebha), de modo que "no se puede inferir un acusado descenso del nivel del mar durante la CSM", hasta el argumento fundamental que favorecería el modelo generalizado de desecación se tambalea. En lugar de una gran cuenca Mediterránea vacía y desecada, "parece que una gran masa de agua persistió posiblemente durante el pico de la crisis" y "no se produjo la desecación completa del Mediterráneo". Tendremos que re-escribir nuestros libros de escuela elemental y del bachillerato.

Revisión crítica histórica

La duración del Mesiniense se duplicó en los 90 en base a bio y cicloestratigrafia datada radiométricamente, más tarde paleomagnéticamente y astronómicamente calibrada. Era necesaria una duración realista del Mesiniense para intentar encajar el período correcto de la cicloestratigrafia registrada.

Las primeras opiniones de una CSM abiótica/oligotípica han sido reemplazadas por los recurrentes influjos del agua marina normal que proporcionaba biotas marinas casi normales. Tales biotas se encuentran en el intervalo lodoso de los pares cíclicos caliza/lodo, yeso/lodo, anhidrita/lodo o sal/lodo visibles en los cortes y los testigos. Por lo tanto tenemos una buena cobertura de biotas y climas de la precesional mínima/insolación máxima de la CSM, pero nos falta información sobre las condiciones climáticas durante la insolación mínima cuando se depositaron los sulfatos y las sales. Así que muchas influencias marinas precisan encontrar cualquier fuente de aguas marinas normales.

La CSM se relacionó a un clima fresco o frio y seco, pero muchos autores sugieren condiciones tropicales templadas. Más tarde el análisis palinológico favoreció "condiciones secas y templadas subtropicales". Adicionalmente no se podían asociar a la CSM cambios climáticos significativos. Esta opinión parece poco coherente con la estratigrafía de isótopos estables oceánicos en el intervalo temporal entre 7.3 y 4.7 Ma (Fig 1). Se conocen dos importantes TG22 y T20 glaciares. Si las interpretaciones palinológicas son correctas, un clima húmedo precisaría una presencia continua de agua en las cuencas mediterráneas, sin descenso y, incluso menos, sin desecación. El actual Mar Caspio está aislado de los océanos mundiales, pero no se ha secado. Además, las litofacies estrictamente evaporiticas de los depósitos cíclicos de la CSM (carbonatos, sulfatos y sales) están todas relacionadas al intervalo frio de los ciclos precesionales.

Es difícil restaurar la paleogeografía del Mediterráneo durante el Mesiniense. Es incierto si los pasillos que unía el Mediterráneo a aguas oceánicas estaban realmente abiertos porque los depósitos marinos diagnóstico podrían estar erosionados o enterrados tectónicamente bajo cabalgamientos; el baipás de agua podría haber ocurrido incluso sin la deposición de sedimentos. Los puntos de vista iniciales excluían las conexiones Mesinienses entre el Océano Índico y el Mar Rojo. Los datos de los sondeos sugieren, sin embargo, que también durante el Mioceno inferior, el Mar Rojo pudo recibir aportaciones parciales de agua marina normal de una fuente oceánica india, necesaria para depositar el manto de sal y yeso en su fondo. En este escenario, el corredor de Suez permite suministrar periódicamente aguas marinas normales superficiales al este del Mediterráneo. Hay dos posibles desagües disponibles, el Golfo de Suez y el rift del Mar Muerto. Hay evidencia para asumir que el norte de Israel (Samaria- Monte Carmelo-Galilea-Golán) estaba todavía *cubierto por el mar hasta los arrecifes poríticos del Mioceno superior (Formación Pattish). El ascenso por bloques de Monte Carmelo comenzó a finales del Mioceno, al mismo tiempo que la intrusión marina del graben de Qishon-Yizre'l hasta el rift del Mar Muerto y el Mar Rojo. Otro desagüe adicional está bajo el cinturón de pliegues cabalgantes de Palmira (exterior de las montañas Zagros) en base a los datos de sondeos que muestran lodolitas marinas pre-punticulata del Plioceno inferior cabalgando sobre sedimentos desde el Neógeno a con punticulata. Esto es coherente con los más de 1000 m de espesor Plioceno de grano fino del ante país de Mesopotamia y el comienzo de los depósitos aluviales gruesos del Éufrates de hace aproximadamente 3.5 Ma, cuando empezó en la zona la elevación y el vulcanismo.*

Los corredores Rifeños y Béticos, todavía activos en flujos interiores y exteriores durante el Tortoniense se redujeron mucho desde el límite del Tortoniense/Mesiniense y especialmente cerca de los 6 Ma (Figura 2). El Guadalhorce (al norte de Málaga) era el último resto del desagüe bético mesiniense que está todavía cubierto por depósitos de corrientes de fondo que fluían del Mediterráneo al Atlántico, una buena evidencia de las conexión en los dos sentidos. La conexión está documentada por foraminíferos planctónicos hasta el Mesiniense inferior (desde hace unos 7.2 a 6.3 Ma), pero pudo durar algo más de tiempo como entradas puntuales que permitían influjos normales periódicos del Atlántico, como para suministrar la deposición continuada de evaporitas en el fondo marino del Mediterráneo y mantener la vida marina normal en las aguas superficiales del Mediterráneo hasta finales del CSM. Por lo tanto, como para los desagües levantinos, pudieron estar disponibles algunas oportunidades de influjos de aguas oceánicas a través de los desagües Béticos y Rifeños durante la mayor parte del CSM.

Las conexiones ParaTétis-Mediterráneo son las más discutidas, especialmente durante la etapa del Mesiniense superior de Lago-Mare (Figura 3).

El ParaTétis centro-occidental (Cuencas de Viena y Pannonia) era ya un lago aislado en el Tortoniense inferior. El ParaTétis centro-oriental estaba conectado al Mediterráneo también más tarde que el Serravaliene, por tres posibles pasillos a través del Mar Mármara-Mar Egeo, la región de la cuenca del Dacia-Tracia-Mar Egeo y la cuenca de Tesalónica-Macedonia-Sofia. La parte más oriental del ParaTétis estaba aislada por la creciente cadena Caucásica. Una elevación media de la cuenca del ParaTétis mas alta que la de los niveles medios del agua en el Mediterráneo, es coherente con una invasión rápida y amplia de toda el área mediterránea por aguas del ParaTétis durante la etapa Lago-Mare al final del Mesiniense.

Se proponen dos mapas paleogeográficos esquemáticos (Figura 2 y 3) para discutir sus principales características paleotectónicas.

- *Las barreras y los umbrales que separaban el Mediterráneo occidental y oriental eran más importantes que las actuales.*
- *Las áreas Mesinienses italianas que afloran hoy son todas parte del Mediterráneo occidental, y muchas de ellas eran menos marginales que como aparecen en un mapa geológico actual. Amplias porciones de los dos arcos Apeninos eran de cuenca con sus contrapartes marginales expuestas a la erosión y el retrabajado.*
- *Todas las áreas Mediterráneas han sido muy afectadas tanto por movimientos horizontales y verticales (Mediterráneo central) y movimietnos verticales (Mediterráneo oriental y occidental) durante el Mesiniense.*

Las marcadas diferencias entre los dos mapas (Figuras 2 y 3) están relacionadas con la tectónica intra-Mesiniense.

Espero que estos mapas estimularán una reevaluación de las diversas interpretaciones generales y locales de la CMS.

Discusión

Una entrada no efímera continuada aunque periódica de aguas atlánticas en una depresión profunda de un supuesto Mediterráneo desecado, habría generado cascadas, rápidas incisiones retrogresivas y una renovada conexión a los océanos, lo que detendría la crisis en unos pocos miles de años. Este proceso espero a producirse hasta la apertura tectónica del corredor de Gibraltar, sugiriendo que el nivel del mar Mediterráneo solo experimentó descensos menores durante la CMS no mayores que las oscilaciones glacioeustáticas de los océanos Atlántico e Índico.

Con una/s desecación/es profunda/as y unos niveles de las balsas de salmueras situadas 2 o 3 km por debajo de los niveles mundiales de los océanos, los niveles de los principales ríos que entraban en el Mediterráneo deberían haber alcanzado un tamaño y unos modelos de relleno claramente diferentes de los de ríos del mismo tamaño y descarga que fluyeran en el océano. Y este no es el caso.

Con descensos de kilómetros, las megasecuencas de yesos inferiores se disolverían rápidamente por las aguas meteóricas y fluyentes a un ritmo de 1 mm/año. Para mantener los ciclos yesíferos conservados como

lo están ahora, la erosión debería hacer sido casi completamente subacuática. Además la desecación profunda debería haber producido en la base de los márgenes continentales y de los fondos del Mediterráneo una cantidad de detritus en un orden de magnitud mucho más abundante que la alcanzada por el lodo Plioceno en un tiempo equivalente. Pero no lo hizo.

El siguiente paso hacia un consenso completo o su completa destrucción parece que depende principalmente de nuevas campañas de sondeos que atraviesen el paquete bandeado del Mesiniense en el Mar Mediterráneo profundo.

Introduction

The controversy on the Messinian Salinity Crisis (MSC), a geo-event formally named by Selli (1960, 1964) but introduced earlier as a concept by the same Selli (1954, p. 86–87, 92–93), occurred more than a decade after the naming of the event. Discussion started in 1973 with DSDP in the Mediterranean as a contrast of generations and as a difference of approach between expert Messinian field and evaporite geologists on one side and newcomer geophysicists and general marine geologists on the other side (see also Drooger 1973). The ensuing harsh debate was polarized accordingly. Later, increasing field research and improved correlation tools, both on land and offshore, have substantially changed and softened the terms of the controversy. What is still under debate today of that controversy, which in the mean time has led to a (diverse) consensus (CIESM 2008, Ryan 2009, Roveri *et al*., 2014a)?

The desiccated whole Mediterranean of the Leg 13 trinity (*i.e.,* K. Hsü, W.B.F. Ryan and M.B. Cita; Hsü *et al*. 1973) has lost supporters. The total Mediterranean isolation is replaced today by increasingly normal marine water supply, with diagnostic faunas and floras still a matter of debate. The scenario has passed from desiccation to normal marine inundations, ingressions, influxes in a mainly hyperhaline water body. These are the new keywords over-flooding more and more what was displayed as a desert. When coining the early name MSC, and later questioning the first simplistic desiccation model in 1973, Selli had actually centred the fundamental parameter, the salinity, of this salt giant, the one which is gradually bringing different authors and models to a consensus. MSC is indeed an inspired, descriptive, non-interpretative term, overcoming any possible falsifying of interpretations. Selli (1973) was also looking far ahead when predicting "both models, even in the same area or basin, can be readily justified" (see Ryan 2009). He was the first to insist that "the majority of Messinian depositional environments in Italy were hyperhaline" in a time when "almost all authors had classified them as brackish or freshwater" (Selli 1954, p. 86–87). More generally, "one would believe that during the late Miocene the whole Western Mediterranean was a huge hyperhaline basin which remained isolated from the Atlantic Ocean or not sufficiently connected to it to maintain its normal salinity" (p. 92). "An isolated Mediterranean, as an enormous hyperhaline lake during late Miocene, is supported also by the Indo-Pacific character of the Miocene marine faunas and the marked Atlantic character of the Pliocene ones" (p. 92–93). All these early statements ended up with definition of the MSC of the Mediterranean (Selli 1960, p. 28).

The major km-deep drawdown of the Mediterranean sea (Hsü *et al.,* 1973, Rouchy and Caruso 2006) is now challenged by a basin-level drop shallower by an order of magnitude (Clauzon *et al*.,1996, Roveri *et al*., 2001, Roveri and Manzi 2006), or even absent (Krijgsman *et al*. 1999b, Hardie and Lowenstein 2004, p. 112; Lu 2006; Lugli *et al*., 2013; Roveri *et al*., 2014b), reviving earlier views (De Benedetti 1976, Sonnenfeld 1985, Sonnenfeld and Finetti 1985).

The former trinity's model, though still appealing, has lost most of its catastrophic potential (Vai 1988b, Benson and Rakic-el Bied 1991), including the geological hazard and risk for large amounts of the population in a geologically near future. When the old point claimed by Selli (1973) and Sonnenfeld (1985) (persistent inflow of marine waters in the Mediterranean) is further elaborated (Krijgsman & Meijer 2008) as to conclude "that no (major) sea-level lowering took place at the onset of the MSC" and that the 'Lower Gypsum' units were consequently deposited in a deep-water Mediterranean basin, the charming desiccation theory is turning into a tale. When the classic marginal Levant canyons are shown to be filled by clastic sulphate facies resulting from subaqueous mass wasting (instead of subaerial sabkha deposits), so that "no pronounced sea-level drop can be inferred during the MSC" (Lugli *et al.,* 2013), even the fundamental argument in favour of the generalized desiccation model staggers. This scenario was already suggested based on the observations that the "Lower Gypsum" deposits accumulated in the deepest settings of both the Apennine and Sicily foreland basins were actually clastic, resedimented deposits emplaced by fully subaqueous gravity flows (Ricci Lucchi *et al*., 1973; Roveri *et al*., 2001; Manzi *et al*., 2005; Roveri *et al*., 2008a). Instead of a great empty desiccated Mediterranean basin, "a large water body likely persisted during the crisis peak" and "there was no full desiccation in the Mediterranean" (Lugli *et al*., 2013; Roveri *et al*., 2014b). These last interpretations definitely give an answer to a major field fact I have observed in most Messinian areas around the Mediterranean. My main question to the deep desiccation theorists since 1973 has been about the frequent occurrence of pre-evaporitic coral reefs, gypsum evaporites, salt, Lago-Mare clastics, and Trubi marls, all at almost the same position in a distal to proximal transect (overlapping landward edges), which would not be expected in the case of a relevant sea-level drop in the Mediterranean basin.

Thus, following the consensus, the Mediterranean was not a desert (or still it was, for a minority of experts, for a much shorter time; Ryan 2009; Bache *et al*., 2009, 2012), and the catastrophe did not occur during the Messinian, nor was delayed for a future opportunity. We will have to rewrite our elementary- and high-school text books, and give less voice to the more and more blaring trumpets of catastrophists. Until a new drilling campaign coring across the entire deep Mediterranean evaporite and able to falsify any previous assumptions and models (Roveri *et al*., 2014a), the 2008 consensus explaining most of the data set is expected to broaden and strengthen an anti-catastrophist scenario (in spite of the close, though minor evidence of a modern actualistic analogue in the Dead Sea saline, counterbalanced, however, by the more normal Red Sea setting).

My aim here is to briefly comment some points of the MSC which have obtained relatively less attention in the last decades, namely the duration of the Messinian age and MSC, the biotas and climate of the MSC, and the Mediterranean palaeogeography of the Messinian compared with the preceding and following settings, especially concerning sills and oceanic water supplies, types of erosion, Mediterranean/ Paratethys connections and the role of tectonics.

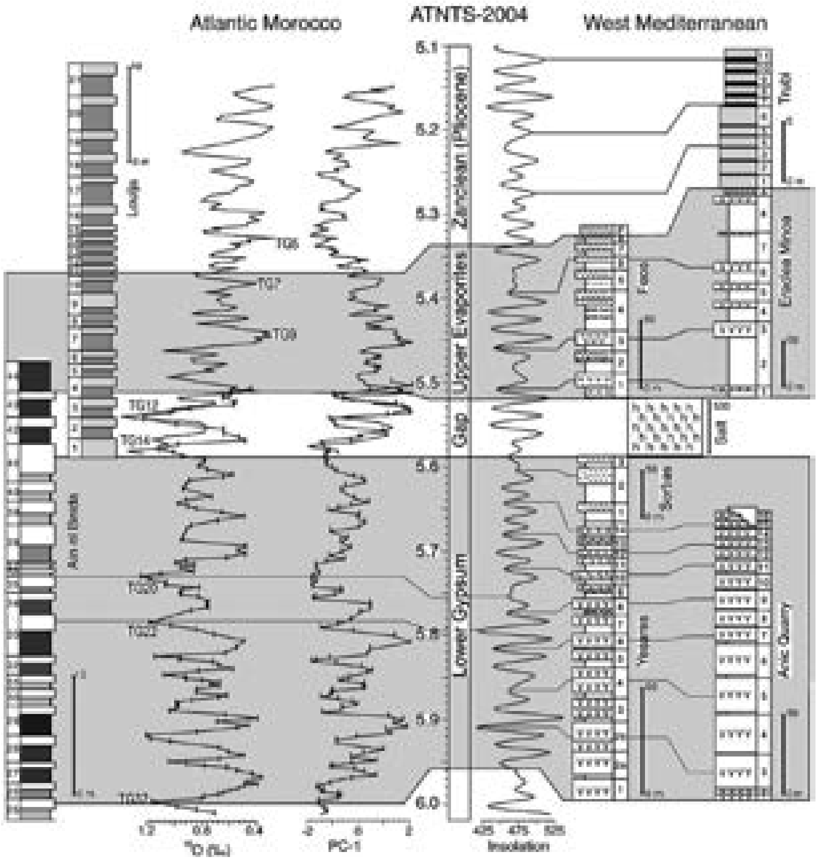

Figure 1. Isotopic astronomic correlation of Messinian key sections from Morocco, Spain, Sicily, and Northern Apennines showing marked glacial and interglacial peaks (TG) (from Krijgsman and Meijer 2008).
Figura 1. *Correlación isotópica astronómica de secciones clave del Mesiniense en Marruecos, España, Sicilia y los Apeninos del Norte, mostrando los picos graciares e interglaciares (TG) (según Krijgsman and Meijer 2008).*

Duration

The Messinian stage as calibrated today between 7.24 and 5.33 Ma (Krijgsman *et al*., 1999a, ratified by IUGS-ICS, see Time Scale Foundation at purdue.edu/Stratigraphy/gssp/) is among the shortest pre-Pleistocene SSS stages, together with the Langhian. However, still at the very beginning of the 1990s the duration of the Messinian was at least 1 Ma less than the present, providing difficult accommodation to the growing amount of stratigraphic and tectonic processes recognized during that time (Vai 1997). It is puzzling to remember that "the Messinian stage lasted about one million years. The salinity crisis had an even shorter duration of about half a million years, spanning the time interval from about 5.7 to 5.2 m.y. B.P." (Hsü, 1986). This was based on Ogniben's (1957) classic cyclostratigraphic estimate of about 120 ka (Tripoli), 95 ka (Calcare di base), 500 to 900 ka (gypsum-sulphur and gypsum-salt) for respective durations. The full cyclostratigraphic potential of the circum-Mediterranean biostratigraphically well-known Messinian sections was clear as soon as reliable radiometric dates were available from the same sections at and close to the Tortonian/Messinian (T/M) boundary. This happened in the early 1990s (Vai *et al*., 1993, Odin 1994, pointing to an age of 7.11±0.20 Ma for the T/M boundary) independently and consistently with the revised calibration of the oceanic magnetostratigraphic scale (Cande & Kent 1992, 1995) in which the T/M boundary was lowered to 6.92±0.02 and 7.11±0.02 Ma respectively (Krijgsman *et al.,* 1994, 1995). After these basic steps doubled the duration of the Messinian age, a much more accurate astronomical calibration of the T/M boundary at 7.24 Ma and dating of many different Messinian events was possible (Hilgen *et al*., 1995, Krijgsman *et al*., 1999a, 1999b). A more realistic duration of the Messinian age in fact was needed for endeavouring the correct forcing period of recorded cyclostratigraphy (Vai 1997). Thus, we were able to constrain the deposition of the salt layer in the deep Mediterranean basin between 5.60 and 5.55 Ma, which is to say within a few precessional cycles (Krijgsman *et al*., 1999a, Hilgen *et al.,* 2007, Krijgsman and Meier 2008; Roveri *et al*., 2008a). This has been obtained and confirmed by several detailed studies of the Messinian evaporites and their associated deposits (Manzi *et al*., 2005; 2007; 2009; 2011) all along the Mediterranean, which led to a refinement of the age of the MSC onset (now placed at 5.971 Ma; Manzi *et al*., 2013) and to a bed by bed astronomically-calibrated correlation of both the Lower Gypsum and Upper Gypsum cycles (Lugli *et al*., 2010, Manzi *et al.,* 2009).

Biotas and climate

Early views of an abiotic (or rarely oligotypic) MSC have been replaced by increasing evidence of recurrent influxes of normal marine water providing almost normal marine biotas, such as fish and mollusc (e.g. Selli 1954 (p. 32–33, 85), Selli 1964, Sturani 1973, Cavallo and Gaudant 1987, Sorbini 1988, Corradini and Biffi 1988, Fourtanier *et al*. 1991, Bertini *et al*. 1998, Carnevale *et al*. (2000, 2006a, 2006b, 2008), Néraudeau *et al*. 2001, Gaudant and Cavallo 2008, Gaudant 2009). A basic remark to all such influxes bearing normal marine faunas and also to samples having supplied palynomorphs (pollen and dinocysts), is that they are found in the muddy interval of the limestone/mud, gypsum/mud, anhydrite/mud, or salt/mud cyclic couplets visible in sections and cores. Thus we have a good coverage of biotas and climate of the precessional minima/insolation maxima of the MSC (Krijgsman *et al*., 1999a) but lack any information about climate conditions during insolation minima when sulphates and salts were deposited. At any rate, amounts and frequencies of documented normal marine influxes, not only close to the Atlantic gateways but everywhere, require searching for any possible source of normal marine water.

Since the beginning, the MSC was related to a cool or cold (Bandy 1973, p. 22, 24) and dry climate, but many authors claimed warm and subtropical conditions. Later palynologic analysis favoured "warm and dry conditions characteristic of tropical to subtropical climates" in the south (Suc & Bessais 1990, Bertini *et al*., 1998), whereas in central and northern Italy humid conditions prevailed under a subtropical climate (Bertini 2006). Additionally, no significant climatic changes were associated with the MSC; "in fact no major changes in vegetal assemblages were recorded before, during and after this event" (Suc & Bessais 1990, Bertini *et al*., 1998, Bertini 2006, Bertini & Martinetto 2011, Cosentino *et al*., 2012). Solely across about 5.5 Ma a drier event has been pointed out by the northward expansion of *Lygeum*, a steppe element, which reached the latitude of Ancona (Bertini 2006). Though echoing earlier opinions (Selli 1954, p. 92), this view seems poorly consistent with ocean stable isotope stratigraphy in the time interval 7.3 to 4.7 Ma (Vidal *et al*., 2002) (Fig. 1). The highest mean $\delta^{18}O$ value (cooler) is reached in the time interval 6.3 to 5.57 Ma, when marked global sea-level drops have been observed. At about 5.56 Ma, a rapid decrease in $\delta^{18}O$ values is documented, which may reflect a global warming period (Vidal *et al*., 2002). The following short salt deposition interval is now related to the

~70 ka time interval between glacials TG14 and TG12 (Krijgsman and Meijer 2008, Roveri *et al*., 2008a; 2014 a,b,c; Shackleton *et al*., 1995), as shown in Figure 1. There, after an initial cooling peaking with the remarkable TG22 and T 20 glacials, a clear upwards warming trend is visible. This sounds surprising when the Messinian in the Mediterranean is represented as a time interval warmer and wetter than the following Pliocene. However, were the palynological interpretations to be correct, the wet climate, wherever present, would require a continuous presence of water throughout the Mediterranean basins, without drawdown and, even less, desiccation. After all, the modern Caspian Sea is isolated from world's oceans, but has not dried up (Butler 2006). Additionally, the strictly evaporitic lithofacies of the cyclic MSC deposits (carbonates, sulphates, and salts) are all related to the cold interval of the precessional cycles (Krijgsman *et al*., 1999a; Manzi *et al.*, 2009; Lugli *et al.,* 2010). Although climate is not considered to have been the main cause of the MSC (otherwise we would have expected its occurrence during the late Pliocene to Pleistocene glaciations) a Messinian climate cooler and dryer than the Tortonian and the early part of the Pliocene has favoured evaporite accumulation.

The common old view quoting only high-salinity tolerant fishes (*Aphanius*), scanty dwarfed foraminifera, and Paratethyan brackish molluscs, dinocysts and ostracodes in the MSC deposits is now radically changed. Bed-by-bed sampling revealed a lot of layers yielding normal and not reworked marine faunas and floras (nannoplancton, dinocysts, planktic foraminifera, nectic fishes). This happens in the lower gypsum megasequence (Vena del Gesso type basins, Cattolica), in the intermediate salt megasequence (Realmonte–Racalmuto), and in the upper gypsum megasequence (Pasquasia, uppermost portion, Manzi *et al*., 2009, 2012; the Tuscany basins, Carnevale *et al.,* 2006a, 2006b). As a consequence, either a connection with the neighbouring Atlantic and Indian oceans or with a satellite normal marine water body has to be assumed, making a pulsating surface- water inflow possible as to supply an aggradation of some mm to dm thick sedimentary layer per cycle on top of the anoxic starved basin-floor materials. Recently, statistical and petrographic studies of the primary cumulate, both halite and gypsum, deposits in Sicily (Manzi *et al*., 2012) suggest that the presence of an annual oscillation of the salinity of the Mediterranean water mass was probably driven by short term climate forcings, mostly related to solar and lunar cycles as previously proposed by Bertini *et al*. (1998, p. 426).

Mediterranean palaeogeography during the Messinian

When speaking about disconnection from and reopening of the global ocean supply to the former Mediterranean water body, usually only the Atlantic Ocean is considered, disregarding any Indian connection. This makes the system extremely rigid, emphasizing apparent inconsistencies and ignoring facts, such as the Indo-Pacific character of the marine organisms during late Miocene in the Mediterranean versus the Atlantic during the Pliocene (Selli 1954, p. 92–93). However, it is always uncertain whether and when gateways were really open because diagnostic marine deposits may have been eroded or tectonically buried under thrust sheets; in some cases, bypass of water may have occurred even without the deposition of sediments.

Oceanic water supply and external to internal sills

Unlike earlier views excluding a Messinian connection between Indian Ocean and Red Sea (Selli 1954, p. 92; and almost all authors since then, such as Adams *et al*.,1983, Vergnaud-Grazzini 1983, Rögl and Steininger 1983, Rögl 1998, 1999), new well data suggest a "major Red Sea-restricted episode of hypersalinity, which is probably related to the partial separation of the Red Sea and Gulf of Suez region from the Indian Ocean and Mediterranean Sea" (Hughes and Beydoun 1992, p. 144). For these authors, deep marine sediments were deposited in both the Gulf of Aden and the Red Sea during the early Miocene. Later, the Red Sea suffered periodic return to hyperhaline conditions during early to middle Miocene, although shallow marine faunas are locally recovered from the southern Red Sea. Thus, "the existence of a partial barrier between the Red Sea and Gulf of Aden is envisaged, possibly in the vicinity of the present-day Bab el Mandeb Straits" (p. 152).Therefore, also during the late Miocene the Red Sea could have been at least partly supplied with the normal marine water, needed to deposit the thick salt and gypsum blanket on its floor, from an Indian oceanic source (see also Meulenkamp *et al*., 2000, p. 196). In this scenario, the Suez corridor is able to supply periodically normal marine surface water to the Eastern Mediterranean (see also Ziegler 1988). Instead, overlooking a Red Sea–Indian Ocean connection, many specialists (e.g. CIESM 2008, p. 20; Ryan 2009, p. 116, 124) found difficulty in explaining differences in seismic facies and thickness of salt deposits in the Western Mediterranean (about 1 km) and the Eastern Mediterranean (about 1.5 km)

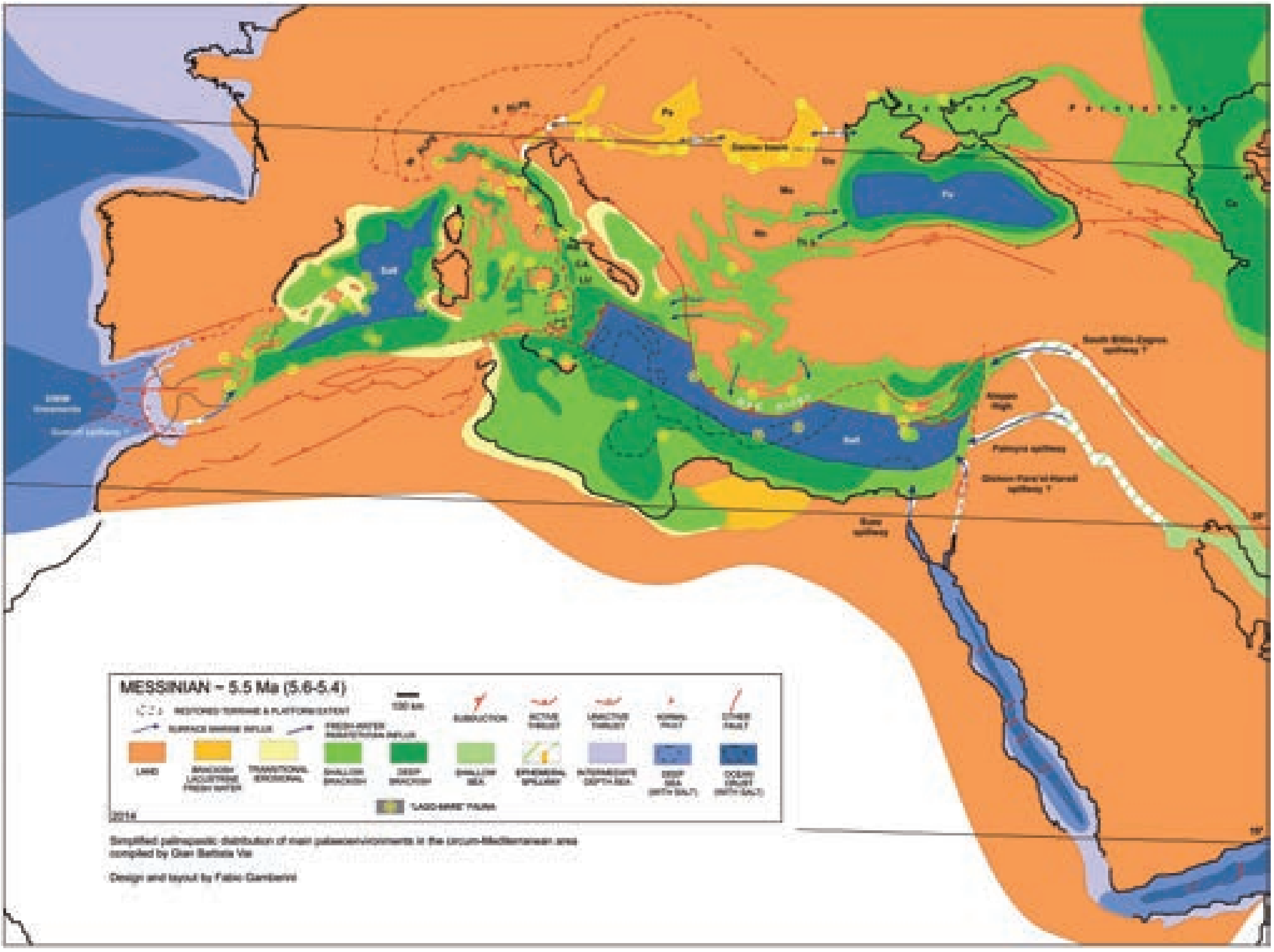

Figure 2. Simplified palaeogeographic palinspastic map of the first Messinian cycle (lower gypsum megasequence) at about 5.8 ± 0.2 Ma. Compiled using data mapped by Argnani (2005, 2012), Barrier and Vrielynck 2008, Esu 2007, Fabbri and Curzi 1979, Gueguen *et al.* 1998, Meulenkamp *et al.* 2000, Meulenkamp and Sissingh 2003, Müller *et al.* 1999, Orszag-Sperber 1993, Patacca and Scandone 2011, Rögl and Steininger 1983, Rögl 1998, Rouchy and Caruso 2006, Ryan 2009, Vai (1988a, 1997), Ziegler 1988. A, Apulia platform. AB, Abruzzi platform. CA, Campania platform. Ca, Caspian basin. Da, Dacian basin. Do, Dobrugia. I, Ionian crust. L, Levant basin. LU, Lucania platform. Mo, Moesia. NC, North Calabria terrane. P, Peloritani terrane, PA, Panormic platform. Pa, Pannon Lake. Po, Pontus-Euxinian basin. SC, South Calabria terrane.
Figura 2. *Mapa palinpastico y paelogeografico del primer ciclo Mesiniense (megasecuencias inferiores yesíferas) hace unos 5.8 ± 0.2 Ma. Compilado utilizando también datos cartografiados por Argnani (2005, 2012), Barrier and Vrielynck 2008, Esu 2007, Fabbri and Curzi 1979, Gueguen et al., 1998, Meulenkamp et al. 2000, Meulenkamp and Sissingh 2003, Müller et al. 1999, Orszag-Sperber 1993, Patacca and Scandone 2011, Rögl and Steininger 1983, Rögl 1998, Rouchy and Caruso 2006, Ryan 2009, Vai (1988a, 1997), Ziegler 1988. A, Plataforma Apulia; AB, Plataforma Abruzzi. CA, Plataforma de Campania. Ca, Cuenca del Caspio. Da, Cuanca Dácica. Do, Dobrugia. I, Corteza Ionianiana. L, Cuenca del Levante. LU, Plataforma Lucaniana. Mo, Moesia. NC, Terrano de Calabria del Norte. P, Terrano de Peloritani, PA, Paltaforma Panórmica. Pa, Lago Pannon. Po, Cuenca Pontico-Euxiniana. SC, Terrano de Calabria del Sur.*

in the assumption that the Atlantic stream should go through the entire Mediterranean to finally reach the Red Sea (over 3 km, Stoffers and Ross 1974) in the far distance. In fact, both the Mediterranean and the Messinian Red Sea evaporites have an oceanic fingerprint (Stoffers and Ross 1974).

As to a connection of the Eastern Mediterranean to the Red Sea and the Indian Ocean during the Messinian, two spillways are available, the Suez Gulf and the Dead Sea rift. Mediterranean marine fauna is present in the Suez area up to the Tortonian (Thiébaud and Robson 1979) and thick Pliocene-Pleistocene sediments are present in the gulf, implying a continued subsidence (Patton *et al.*, 2000, p. 32) allowing periodic marine influxes also with Indian faunal affinity since the Messinian (Richardson and Arthur 1988). This is consistent with the thick Miocene subaqueous evaporite deposits (Orszag-Sperber *et al*., 1993 (p. 250). Gvirtzman *et al*., 2011 (Fig. 13) and Meulenkamp *et al*. 2000 (p. 200) provide good reason to assume that N Israel (Samaria-M. Carmel-Galilee-Golan) was still covered by the sea up to late Miocene poritid reefs (Pattish Fm). The M. Carmel block uplift began in the late Miocene coeval with marine invasion of the Qishon-Yizre'l Graben down to the Dead Sea rift and the Red Sea.

An additional spillway is to be looked for in N Syria, beneath the Palmyra fold and thrust belt (outer Zagros mountains) (from the Antalya basin through the Beotian trough to the Euphrates foredeep and the Persian Gulf). At the end of the last century confidential well data provided evidence of early Pliocene pre-*G. punticulata* marine mudstone thrusted over Neogene to *G. puncticulata*-bearing sediments in the NW Palmyra fold and thrust belt. There, a 20-km wide strip of late Miocene to early Pliocene marine environment should be admitted, being now mostly buried under early Pliocene thrusting (see also Scott 1981 and Chaimov *et al*.,1992). This is consistent with the over 1000 m thick fine grained Pliocene of the Mesopotamia foredeep and the beginning of the Euphrates coarser alluvial deposits at about 3.5 Ma when uplift and volcanism began in the area (Trifonov *et al*., 2013). Indian marine influxes are also common within the evaporite succession of the Arabian platform throughout the Miocene (Buchbinder and Gvirtzman 1976, Al-Hashimi 1979). A final spillway connecting the Levantine basin to the Indian ocean from the Antalya basin through E Anatolia-Van Lake to Makran Gulf and Indian ocean was also suggested (Sonnenfeld 1977) but later disputed (Hüsing *et al*., 2009).

West of Suez, the classic Rifian and Betic corridors (Selli 1954) still active in out- and inflow during Tortonian (Orszag-Sperber *et al*., 1993, Meulenkamp *et al*. 2000, CIESM 2008) were severely reduced since the Tortonian/Messinian boundary (about 7.2 Ma) (Roger *et al.,* 2000, Kouwehoven and van der Zwan 2006, Zitellini *et al.* ,2009) and especially near 6 Ma (Krijgsman *et al*., 1999b). The Guadix basin in the Central Betic Cordillera connected the Atlantic through the Guadalquivir basin to the Mediterranean by means of the two Capo Coy and Almanzora gateways (Fig. 2). Late Tortonian shallow to deep marine deposits are still exposed, and were followed by uplift closing the connection at the Tortonian/Messinian boundary (~7,2 Ma) (Soria *et al*., 1999, questioned by (Hüsing *et al*., 2010), as a result of tectonic transition from convergence to extension. From 6.3 Ma uplift in the Guadalquivir basin and the Gibraltar area brought the isolation of the Mediterranean, interrupted by subsidence in the Gibraltar area at the end of the Messinian (Sierro *et al*., 2008, p. 47). The Guadalahorce corridor (N of Malaga) was the last remaining Messinian Betic gateway, which is still floored by deposits of bottom currents flowing from the Mediterranean into the Atlantic (Martin *et al*., 2001), good evidence of the two-way connection. This gateway was up to 5 km wide and up to 120 m deep. Connection is documented by planktic foraminifera up to early Messinian (about 7.2 to 6.3 Ma) (Martin *et al*., 2001), but may have lasted longer as punctuated inflows allowing for periodic normal marine influxes from the Atlantic, so as to supply continued evaporite deposition on the Mediterranean sea floor and maintain normal marine life in the Mediterranean surface water layer until the end of the MSC (Carnevale *et al*., 2000, 2006a, 2006b, 2008).

Thus, as in the Levantine gateways, some chance of oceanic water influxes through the Betic and Rifian gateways during most of the MSC should have been available.

With the Pliocene, Indian to Mediterranean connections were progressively severed and closed, following the increased convergence rate of the Arabian plate with about 100 km sinistral movement along the Dead-Sea transform. Unlike Blanc's (2000, p. 1455) opinion, it appears that regional tectonics rather than erosion plays the critical role in opening and closing gateways. The Rifian corridors (Querrah and Saïss–Guercif) (Esteban *et al*, 1996) lasted a slightly longer until about 6 Ma (Krijgsman *et al*., 1999) leading after that time to the substantial isolation of the Mediterranean. Similarly, the abrupt opening of the Gibraltar Strait at the beginning of Pliocene was probably forced by an early E-W trending activation of the later WNW-ESE oriented SWIM lineament (Zitellini *et al*., 2009) (Fig. 3).

Paratethys-Mediterranean connections are the most debated especially during the latest Messinian Lago-Mare stage (Fig. 3). As to the Lago-Mare Paratethyan fauna, it is worth recalling that as early as the mid 19th century Scarabelli (1851), the true pioneer of modern Tertiary and Quaternary stratigraphy of the Northern Apennines from Emilia to Marche regions, established the Miocene age of the evaporates, providing detailed stratigraphy of gypsum strata overlain by schizoid cherty carbonates with *Paludina* and other freshwater and brackish fauna (p. 244–246) unconformably overlain by the Pliocene blue clay. All this inspired Capellini (1868) to correlate for the first time the late Miocene brackish/freshwater fauna on the top of the Apennine evaporites with the Paratethyan Pontian fauna he had sampled in Wallachia and Crimea (p. 35–36), later importing the name *Congeria* beds into the Mediterranean area (Capellini 1874, p. 81, Tav. I).

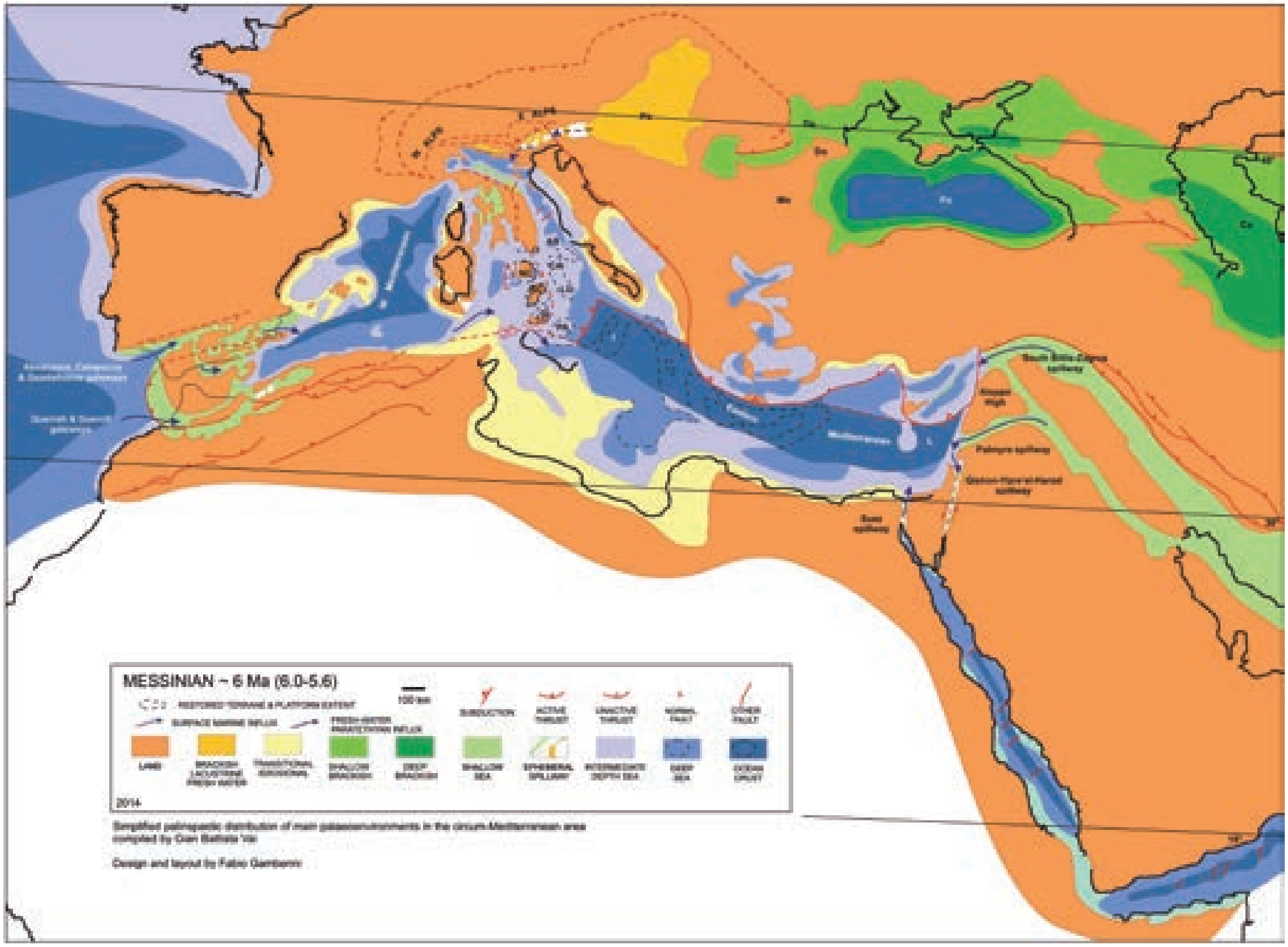

Figure 3. Simplified palaeogeographic palinspastic map of the second Messinian cycle (upper gypsum megasequence up to Colombacci and Lago-Mare type deposits) at about 5.5 ± 0.2 Ma. Compiled using data mapped also by Argnani (2005, 2012), Barrier and Vrielynck 2008, Esu 2007, Fabbri and Curzi 1979, Gueguen et al., 1998, Meulenkamp *et al.* 2000, Meulenkamp and Sissingh 2003, Müller *et al.* 1999, Orszag-Sperber 1993, Patacca and Scandone 2011, Rögl and Steininger 1983, Rögl 1998, Rouchy and Caruso 2006, Ryan 2009, Vai (1988a, 1992, 1997), Ziegler 1988. A, Apulia platform. AB, Abruzzi platform. CA, Campania platform. Ca, Caspian basin. Da, Dacian basin. Do, Dobrugia. I, Ionian crust. L, Levant basin. LU, Lucania platform. Mo, Moesia. NC, North Calabria terrane. P, Peloritani terrane, PA, Panormic platform. Pa, Pannon Lake. Po, Pontus-Euxinian basin. SC, South Calabria terrane.

Figura 3. *Mapa paleogeográfico palinspatico simplificado del segundo ciclo Mesiniense (megasecuencia superior yesífera hasta los depósitos tipo Colombacci y Lago_Mare) hace 5,5 ± 0,2 Ma. Compilado utilizando también datos cartográficos de Argnani (2005, 2012), Barrier and Vrielynck 2008, Esu 2007, Fabbri and Curzi 1979, Gueguen et al., 1998, Meulenkamp et al. 2000, Meulenkamp and Sissingh 2003, Müller et al. 1999, Orszag-Sperber 1993, Patacca and Scandone 2011, Rögl and Steininger 1983, Rögl 1998, Rouchy and Caruso 2006, Ryan 2009, Vai (1988a, 1992, 1997), Ziegler 1988. A, Plataforma Apulia; AB, Plataforma Abruzzi. CA, Plataforma de Campania. Ca, Cuenca del Caspio. Da, Cuenca Dácica. Do, Dobrugia. I, Corteza Ionianiana. L, Cuenca del Levante. LU, Plataforma Lucaniana. Mo, Moesia. NC, Terrano de Calabria del Norte. P, Terrano de Peloritani, PA, Paltaforma Panórmica. Pa, Lago Pannon. Po, Cuenca Pontico-Euxiniana. SC, Terrano de Calabria del Sur.*

The central-western Paratethys (the Vienna and Pannonian basins) was already an isolated lake in early Tortonian (Rögl & Steininger 1983, Magyar *et al.*, 1999, Müller *et al.*, 1999), but may have experienced punctuated connections to the Dacic basin during late Messinian (Clauzon *et al.*, 2005, Esu 2007). This was the main effect of the post-convergence uplift of the E Alps and N Carpathians before the Pliocene–Quaternary collapse of the central Pannonian depression and the uplift of the eastern and southern Carpathians. The central eastern Paratethys was connected to the Mediterranean by three possible gateways through the Marmara Sea–Aegean Sea (Çağatay *et al.*, 2006), the Dacian basin–Thrace–Aegean Sea region, the Thessaloniki–Macedonia–Sofia basin (Clauzon *et al.*, 2005) or even the Balkans–Skopje region, also later than Serravallian (Rögl and Steininger 1983). This occurred as a consequence of the back-arc extension in the Aegean area. However, both Selli (1954) and Clauzon *et al.* (2005) delay the opening of Dardanelles Strait to the Quaternary or Pliocene. The easternmost Paratethys was isolated by the growing Caucasus chain. We have suggested that a freshwater corridor connected the Pannonian–Slovenian basin to the Friuli thrust-top continental basin and the N Adriatic foredeep-foreland marine basin via the outermost present Julian–Karawanken foothills that were thrusted and uplifted only since late Pliocene time (Vai 1988a, p. 28–31; Marabini and Vai 1988, p. 52). This view is supported by the purely freshwater Paratethyan character of the Messinian deposits in the Venetian foothills and plain, the only Italian area devoid of Messinian evaporates (as stage 3 in the Western Mediterranean, Manzi *et al.*, 2009). The following early Pliocene flooding drew the same area (e.g. Cornuda in the Venetian plain), but could not reach the Pannonian basin, which is suggested to have been higher than the Mediterranean water level. Thus, even during most of the Messinian the N Adriatic area may have acted as an entry point for the formation of deep Mediterranean cold water (Kouwenhoven & Van der Zwaan 2006, Gennari *et al.*, 2013) collecting most of the draining system of the Alps, especially the palaeo-Danube, consistent with the Late Pliocene–Early Pleistocene age of the modern hydrographic network in Dacia (Jipa 1997). More generally, a mean elevation of the Paratethys basins higher than the Mediterranean water level is consistent with the rapid and wide invasion of the whole Mediterranean area by Paratethyan waters during the Lago-Mare stage at the end of Messinian. As for Messinian nannoplancton and other marine organisms found on both sides of the Dardanelles (Orszag-Sperber *et al.*, 1993) and in the Dacian basin (Clauzon *et al.*, 2005, although not yet confirmed), they could have derived from punctuated influxes of normal Indian waters via the Eastern Mediterranean and Aegean seas. The persistence of marine connections between the Mediterranean and the Atlantic, albeit reduced, could have also persisted during the third stage of the MSC as suggested by Manzi *et al.* (2009) and witnessed by the occurrence of long chain alkenones (Mezger, 2012), "dwarf" foraminifers (Iaccarino *et al.*, 2008) and calcareous nannoplankton (Rouchy and Caruso, 2006; see Roveri *et al.*, 2014a).

Palaeogeography

An attempt was made to produce a picture of the palinspastic geography and dynamics of the Messinian times in the Mediterranean more realistic than currently available. Two time slices encompassing each of most of the two main MSC cycles (Ryan 2009) or stages recently well characterized in terms of Sr isotope values as well (stages 1+2 vs 3.1+3.2) (Roveri *et al*, 2014 a,b,c) were selected (Figs. 2, 3). The sketch maps, open to be improved by regional experts, are quite different from the few previous attempts, especially as far the palaeotectonic main features are concerned.

- In general, barriers and sills separating the western from the eastern Mediterranean were more prominent than today.
- The Italian Messinian areas largely outcropping today were all definitely part of the eastern Mediterranean, and many of them were far less marginal than they appear on a present day geological map. Wide portions of both Apennine arcs were clearly basinal with their marginal counterparts largely exposed to erosion/reworking.
- All Mediterranean areas have been strongly affected by both relevant horizontal and vertical (central Mediterranean) or mainly vertical movements (western and eastern Mediterranean) during the Messinian.

The difference between the two maps is remarkable (Figs. 2, 3) in spite of the short time span separating them, 0.5 Ma only. This is mainly related to the intra-Messinian tectonics affecting the different basins in different ways, with overlapping effects of orogenic arc migration, Ionian crust subduction, and African plate rotation towards Europe.

If we accept the view of minor climatic change between the two main cycles/stages of the MSC, then the late Messinian Lago-Mare facies (Bertini 2006, Esu 2007, Gliozzi *et al.,* 2007) appears to have been driven more by quite abrupt Paratethyan flooding and organism migration rather than a simple higher inflow of local fresh water.

Hopefully, these new maps will stimulate a reappraisal of the different general and local interpretations of the MSC.

Discussion

Some critical remarks and comments to the previous review are required.

A non ephemeral almost continued, though periodic Atlantic water inflow into an inferred desiccated (some km-deep) Mediterranean depression had certainly generated waterfalls, rapid retrogressive incision and a deeper two-way renewed connection to the Atlantic and Indian oceans, halting the crisis in a few millennia. If this process waited to occur until the tectonic opening of the Gibraltar corridor, it suggests that the Mediterranean sea level underwent only minor recurrent drawdown during the MSC not much stronger than the Atlantic and Indian glacio-eustatic ocean-level oscillations. In fact, some N Betic spillways now filled by Pliocene shallow marine deposits (less than 100 m deep, the Nijar, Carboneras and Murcia basins, Meulenkamp *et al.*, 2000b, p. 204) probably allowed Atlantic marine influxes forced by glacio-eustatic oscillations of about 50 m amplitude to overflow the Mediterranean starved waters during the Messinian. Thus, 50 to 100 m must have been the magnitude of evaporative fluctuations of the Mediterranean sea level at the same time. However, one should not move from an excess to the opposite one. Quite severed and limited influxes of normal marine Atlantic waters have to be admitted as a basic and triggering factor of the MSC. Having additional similar inflow into the Mediterranean from the Indian Ocean by different spillways periodically active through the entire Messinian and definitely constricted only during Pliocene thrusting and uplift is useful to explain the thickness of the evaporites and the provincial affinity of the biotas.

The point of incised valleys and south Alpine lakes as effects of the inferred deep Messinian drawdown was always debated regarding the true age and environment of incision, and the age and texture of the infill material. With deep desiccation(s) and the level of the brine pools located 2 to 3 km lower than world sea level (Cita *et al.*, 1999) the major rivers flowing into the Mediterranean should have reached the size and pattern of filling definitely different from rivers of similar size and discharge flowing into the ocean. This is not the case when comparing, for example, the Rhone and Ebro with the Seine, Rhein, and Garonne in the Piacenzian map (Meulenkamp *et al.*, 2000), in spite of some opposing views. This strongly supports the new interpretation of the Levant (Lugli *et al.*, 2013) as well as of the other Messinian canyons (Roveri *et al.,* 2014b) disproving an over a 100 m deep Messinian drawdown.

An additional comment about inferred sub-aerial erosion in the context of deep multi-desiccated Mediterranean basin is important. The first MSC cycle (stage 1-PLG by Roveri *et al.*, 2008a; 2014a) or lower gypsum megasequence would be quickly dissolved by meteoric and running waters at a rate close to 1 mm/a (Cucchi *et al.*, 1998), especially in the marginal basins. For the gypsum cycles to be preserved as they are, erosion must have been mostly or completely subaqueous. Moreover, deep desiccations should have produced at the base of continental margins and on the Mediterranean floors an amount of detritus an order of magnitude thicker than the one reached by the Pliocene ooze for an equivalent time. However, this is disproved by the seismic lines (Lofi *et al.*, 2005). Additionally, such a detritus should contain clasts of different age and rock types. Instead, only gypsum detritus was found (see also Butler 2006 and Ryan 2009, p. 112) which makes subaqueous mass wasting and sliding of partly unconsolidated Messinian sediments only possible as observed in onshore Messinian successions (Roveri *et al.*, 2001, 2008a; Manzi *et al.*, 2005). It is worth noting that all along the Mediterranean basin margins the beginning of stage 2 (CIESM 2008; Roveri *et al.*, 2008a, 2014a) is marked by a strong tectonic activity marked by a regional-scale angular unconformity at the top of the Primary Lower Gypsum unit of stage 1, known as Messinian erosional surface (MES), flooring a complex evaporite unit largely composed by subaqueous clastic evaporites (resedimenting the PLG deposits) and by deep-water primary cumulates (both gypsum and halite).

The next step towards a complete consensus or its breaking apart again seems mostly dependent upon a new drilling campaign across the whole layered Messinian package in the deep Mediterranean Sea.

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