Earth and Planetary Science Letters 472 (2017) 25–37

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Quantifying the Mediterranean freshwater budget throughout the late Miocene: New implications for sapropel formation and the Messinian Salinity Crisis

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A R T I C L E I N F O

Article history:
Received 13 October 2016
Received in revised form 6 March 2017
Accepted 9 May 2017
Available online xxxx
Editor: H. Stoll

Keywords:
Mediterranean Sea
Messinian Salinity Crisis
sapropel
Chad-Eosahabi
astronomical tuning
modelling

A B S T R A C T

The cyclic sedimentary record of the late Miocene Mediterranean shows a clear transition from open marine to restricted conditions and finally to evaporitic environments associated with the Messinian Salinity Crisis. This evolution has been attributed to changes in Mediterranean–Atlantic connectivity and regional climate, which has a strong precessional pulse. 31 Coupled climate simulations with different orbital configurations have been combined in a regression model that estimates the evolution of the freshwater budget of the Mediterranean throughout the late Miocene. The study suggests that wetter conditions occur at precession minima and are enhanced at eccentricity maxima. We use the wetter peaks to predict synthetic sapropel records. Using these to retune two Mediterranean sediment successions indicates that the overall net freshwater budget is the most likely mechanism driving sapropel formation in the late Miocene. Our sapropel timing is offset from precession minima and boreal summer insolation maxima during low eccentricity if the present-day drainage configuration across North Africa is used. This phase offset is removed if at least 50% more water drained into the Mediterranean during the late Miocene, capturing additional North African monsoon precipitation, for example via the Chad-Eosahabi catchment in Libya. In contrast with the clear expression of precession and eccentricity in the model results, obliquity, which is visible in the sapropel record during minimum eccentricity, does not have a strong signal in our model. By exploring the freshwater evolution curve in a box model that also includes Mediterranean–Atlantic exchange, we are able, for the first time, to estimate the Mediterranean's salinity evolution, which is quantitatively consistent with precessional control. Additionally, we separate and quantify the distinct contributions regional climate and tectonic restriction make to the lithological changes associated with the Messinian Salinity Crisis. The novel methodology and results of this study have numerous potential applications to other regions and geological scenarios, as well as to astronomical tuning.

1. Introduction

At present, net evaporation and cooling increases the density of Mediterranean surface water, making it sink and ventilate the water column. This process of deep-water formation establishes a density gradient between the Mediterranean and the Atlantic, which drives anti-estuarine exchange at the Strait of Gibraltar (Rohling et al., 2015 and references therein). The Mediterranean sedimentary record demonstrates that this circulation pattern has not always been active. Atypical marine deposits occur in the form of organic-rich sediments (sapropels, Kidd et al., 1978), which populate the Mediterranean succession from the middle Miocene onwards (Rohling et al., 2015 and references therein), as well as by evaporites, which were precipitated during the Messinian Salinity Crisis (MSC; Roveri et al., 2014 and references therein). The occurrence of these anomalous sediments has been linked to changes in climate and Atlantic–Mediterranean connectivity. Sapropel formation is thought to occur due to stratification of the Mediterranean water column and enhanced surface productivity (e.g. Rohling et al., 2015 and references therein). These are generally considered to be related to a northward shift of the Intertropical Conver-

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http://dx.doi.org/10.1016/j.epsl.2017.05.013

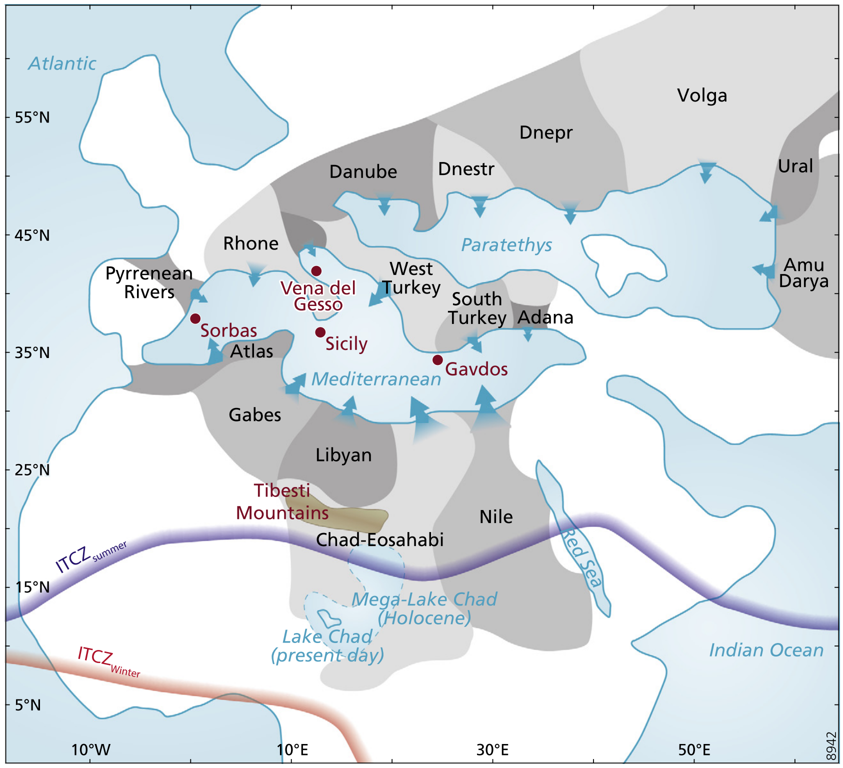

Fig. 1. Schematic palaeogeographic map of the Mediterranean region during the late Miocene, based on Markwick (2007). Indicated are rivers that drained or might have drained into the Mediterranean during the late Miocene, their catchment areas (schematic, following Gladstone et al., 2007), the present-day northern hemisphere summer and winter Intertropical Convergence Zone (ITCZ) and relevant field sections/areas (red). On a side note, the position of the summer ITCZ plotted is approximately the position of the summer ITCZ at precession maxima and the winter ITCZ plotted is approximately the summer ITCZ at precession minima (Marzocchi et al., 2015). In the GCM the Atlantic Ocean has been disconnected to capture the restricted basin behaviour of the Mediterranean Sea during the MSC. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

gence Zone (ITCZ, Fig. 1) during precession minima, when more North African monsoon rainwater contributes to the Mediterranean freshwater budget (Rossignol-Strick, 1983), but sapropels may also develop during rapid global sea-level fluctuations causing changes to the Mediterranean–Atlantic connectivity (e.g. Grant et al., 2016; Hennekam, 2015). The substantial volumes of Messinian gypsum and halite are indicative of a much higher Mediterranean salinity than today. Possible triggers for brine concentration consistent with evaporite precipitation include eustatic restriction of the Mediterranean connection with the global ocean, and/or tectonic changes in the gateway region (see Flecker et al., 2015), together with strong, net evaporative loss across the basin surface.

To date, neither the gateway evolution, nor the past Mediterranean freshwater budget evolution have been quantitatively constrained. Previous studies of the freshwater budget have either (1) assumed it was constant, and used the present day value (Blanc, 2000); (2) used a budget derived from a late Miocene idealised Atmospheric General Circulation Model (AGCM) simulation by Gladstone et al. (2007) (e.g. Simon and Meijer, 2015); (3) assumed that the freshwater budget is driven by fluvial discharge and changes linearly in phase with summer insolation at 65°N (e.g. Hennekam, 2015); or (4) that fluvial discharge varies as an idealised sine function (Topper and Meijer, 2015). All these studies assume that changes in the freshwater budget control sedimentation (Ryan, 2008) and astronomical tuning uses this concept to date sedimentary successions with an accuracy on precession scale (e.g. Hilgen and Krijgsman, 1999).

Here, by contrast, we calculate a freshwater evolution for the Messinian (7.25–5.33 Ma) using a novel multi-model approach, which is based on fully coupled climate model simulations rather than on summer insolation at 65°N. This allows us to estimate the variation in precipitation (P), evaporation (E) and river discharge (R) throughout the Mediterranean region over the entire late Miocene and hence, to disentangle gateway and climate effects on the Mediterranean's environmental evolution for the first time. High temporal (∼1 kyr) quantitative results are derived from an ocean-atmosphere-vegetation General Circulation Model (GCM; HadCM3L; Marzocchi et al., 2015). These GCM results are extended through time using a regression model (RM) to estimate the freshwater budget. Assuming that a simple threshold value of the freshwater budget controls sediment type, we use the budget curve to calculate the pre-MSC sapropel pattern and compare it with late Miocene sapropel-bearing successions exposed in southern Spain (Abad composite, Sorbas, western Mediterranean) and Sicily (Falconara, central/eastern Mediterranean). We also apply the curve to an investigation of the environmental changes that occurred at the onset of the MSC using a box model developed by Meijer (2006). Fig. 2 illustrates how the various components of this study interconnect. Our approach provides a new way to study the relationship between insolation, the Mediterranean freshwater budget and astronomical tuning. It provides new insights into the conditions under which sapropels and evaporites form and helps distinguish the role of the Mediterranean freshwater budget in generating the region's environmental evolution from changes in Mediterranean–Atlantic connectivity.

2. Model hierarchy

2.1. General Circulation Model (GCM)

All numerical simulations are carried out using the UK Met Office General Circulation Model (HadCM3L version 4.5, see Valdes et al., submitted for publication and references therein for a full description), which is coupled to the TRIFFID vegetation model