Abstract

The Mediterranean area is one of the most appealing natural laboratories in the world to study geodynamic and paleoclimatic processes on different scales. Consequently, the Mediterranean Sea can be considered as the Mare Nostrum ('our sea') of Earth sciences. Its semi-enclosed land-locked configuration in a convergent setting between Africa in Europe, in combination with its latitudinal position, makes the Mediterranean extremely suitable to study both fundamental plate tectonic processes and astronomically induced oscillations in climate. For many years to come, the Mediterranean will certainly remain a fascinating area, where an integrated and multi-disciplinary approach will increasingly contribute to our understanding of geological, geophysical, geodetical and geochemical processes in an accurate and high-resolution time-frame.

Keywords: Mediterranean region; geodynamics; paleoclimate; Miocene; gateways

1. Introduction

Ever since the ascent of western civilization (about 3–4 kyr ago) the Mediterranean has been a sea of mystery, leaving most societies puzzled about the origin and evolution of the world on which they lived. Earth scientific processes had major impact on Mediterranean history as complete cities and civilizations have been destroyed by volcanic eruptions, destructive earthquakes and rapid subsidence (e.g. Atlantis, Pompei, Izmit, Minoans) while entire subcontinents may have been drowned during the dramatic sea-level rise of Noah’s flood [1]. In the early days, these catastrophies were ascribed to the activity of angry gods, but only since the advent of the theories of plate tectonics and astronomical forcing of ice ages (less than 0.05 kyr ago) may we confidently say that we are beginning to understand the underlying mechanisms and geological processes. Subsequently, the Mediterranean has always been one of the best natural laboratories in the world to study the fundamental geodynamic and paleoclimatic processes of the Earth. According to the myth of Odysseus, the Greeks’ voyages of adventure were among the first to explore all corners of the Mediterranean Sea. The only way out was through the so-called Pillars of Heracles in the west. If this narrow strait (of Gibraltar) was to be passed one would enter the exterior oceans and chances of returning were thought to be minimal (Fig. 1). It is exactly this land-locked configuration of the Mediterranean which largely controls...
its geologic processes and which also makes it such a unique recorder of past climate variations. During the last decade, the Mediterranean area has been the source of new insights of geodynamic and paleoclimatic processes on Earth. The complexity of the tectonically active land-locked Europe–Africa collision zone (Fig. 1) provides the opportunity to study and understand fundamental plate tectonic processes, like arc migration, slab roll-back and slab detachment, in different evolutionary stages of subduction zones [2]. In addition, the semi-enclosed configuration in combination with its latitudinal position makes the Mediterranean particularly sensitive to record, in the geological archive, astronomically induced oscillations in climate [3]. Today, the functioning of the Mediterranean Sea largely depends on the water exchange with the open ocean and, as such, on the geometry of the Strait of Gibraltar [4]. Consequently, the paleogeographic evolution of the Atlantic gateway is crucial for understanding the temporal and spatial distribution of sedimentation patterns in the Mediterranean basins in terms of both the geodynamic and environmental (oceanographic, climatic) evolution. This is especially evident in the ongoing debates on the processes that have led to the ‘Messinian Salinity Crisis’, a dramatic event during which the water exchange with the Atlantic was strongly reduced and finally cut off, leading to kilometers thick evaporite deposits in a largely desiccated Mediterranean basin [5,6].

This paper reviews the most recent progress made in our understanding of the geodynamic and paleoclimatic processes in the Mediterranean area. For this, the Mediterranean Sea is temporarily regarded as our ‘omphalos’, the center of the world, like the ancient Greeks did earlier when placing their omphalos in the city of Delphi. This is justified as the Mediterranean is not just the cradle of modern civilization or a nice holiday resort for tired earth scientists, but also a highly dynamic area which contains many answers to fundamental earth scientific questions locked inside its well-preserved geological records.

2. Mediterranean geodynamic evolution

The geodynamic evolution of the Mediterranean has been largely determined by the convergence of Europe and Africa, resulting from differential spreading along the Atlantic oceanic ridge. As a consequence, the African plate collided with Eurasia while its gravitationally unstable oceanic lithosphere slowly subducted under the European margin. The total convergence can be estimated at 400–500 km in the west to about 1500 km in the east, and led to the orogenic Alpine build-up as well as to the consumption of the former Tethys

![Fig. 1. Reconstruction of the Mediterranean area according to the Roman map of Marcus V. Agrippa (A.D. 20) and the plate boundary evolution map of Wortel and Spakman [2] (A.D. 2000).](image-url)
ocean. In spite of convergence acting as the primary plate tectonic process, the Mediterranean is also known for its large-scale extensional basins and its diverse tectonic arcs. They are mainly the result of the typical land-locked configuration of the Mediterranean region, in which slab roll-back of the trench systems induced arc migration and extension in the lithosphere above the subduction zone [2]. Most of our knowledge on subduction zones comes from present-day data, such as earth-
quakes in Benioff zones or tomographic images, which trace out snapshot images of subducting slabs (Fig. 2c). Seismic tomography models of the Mediterranean and surrounding regions have been fundamental for locating and delineating the subducted lithosphere [2,7]. They suggest that not all slabs are connected to the lithosphere at the surface, which has been interpreted as an indication for slab detachment. Slab detachment can also migrate laterally since a small tear in the slab will initiate lateral rupture propagation [2].

2.1. The Hellenic arc and the Aegean basin

In the eastern Mediterranean, the rotation motion of the African plate led to the closure of the connection between the Tethys and the Indian Ocean by the collision of the Arabian microplate with stable Eurasia in the middle Miocene (Fig. 1). Disruption of this seaway had a profound effect on oceanic circulation patterns and caused a major change in global climate into a much colder mode (ice house state), while the ocean system rapidly progressed towards modern conditions [8]. The Aegean region represents a piece of continental lithosphere undergoing widespread extension in the general frame of Africa–Europe convergence. Most geodynamical models for the eastern Mediterranean consider the initiation of extension in the Aegean area as a direct consequence of southward migration of the Hellenic subduction zone and/or lateral extrusion of Anatolia away from the Arabia–Eurasia collision front [9]. The minimum age for the onset of extension on the scale of the whole Aegean is estimated at about 20 Ma, based on recent studies within the Cenozoic metamorphic complexes [10]. This implies that the Aegean extension did not result from the lateral extrusion of Anatolia, because the indentation of Arabia into Eurasia is thought to have occurred less than 16 Ma. In addition, numerical modelling of the stress field and deformation also indicated that the role of the lateral push of Anatolia is secondary to that of slab roll-back in a land-locked basin setting [11]. Paleomagnetic data from the entire Hellenic outer-arc indicate clockwise rotations in the western and counter-clockwise rotations in the eastern Hellenic arc [12]. These block rotations in the Aegean have now been accurately dated and point towards a very rapid and young (Pleistocene) rotation phase. New space-based geodetic techniques – the Global Positioning System (GPS) and interferometric synthetic aperture radar (INSAR) – are now capable of mapping crustal deformation with centimeter precision [13,14]. These geodetic observations indicate that the rotational movements in the Aegean area continue even today (Fig. 2a). Physical experiments that simulate the horizontal spreading of a continental lithosphere toward a free boundary are also in good agreement with the observed rotations (Fig. 2b; [10]).

2.2. The Calabrian arc and the Tyrrhenian basin

The opening of the western and central Mediterranean took place mainly in the last 30 Myr by two rapid episodes of trench migration and back-arc opening, which consumed the westernmost extension of the Tethys and created the small oceanic basins we see today (Fig. 1). During the first episode, the Algero–Provencal basin opened as a result of radial back-arc extension caused by roll-back of a subducting slab. This phase was accompanied by the counter-clockwise rotation of the Corsica and Sardinia blocks, possibly including the Epiligrurian units of the northern Apennines of Italy as well [15]. The rotation ended somewhere in the Langhian (±16 Ma) and was followed by slab detachment along the northern African margin, according to the model of Carminti et al. [16]. Secondly, an eastward shift of active extensional deformation resulted in the opening of the Tyrrhenian basin during the Tortonian to Quaternary. GPS data shows that the outward migration of the Calabrian arc has nowadays almost ceased [14], which supports the conclusion that slab detachment processes under Calabria have just been completed [2]. Recently developed laboratory experiments show that the fast and episodic retreat of the subducting slab is dynamically consistent with the gravity-driven subduction of an oceanic lithosphere interacting with the 670-km discontinuity in the upper mantle ([17]; Fig. 2d).
2.3. The Gibraltar arc and the Alboran basin

The geodynamic evolution of the Gibraltar arc is still subject to controversy. Much of the debate is focused on the mechanisms required to generate rapid late-orogenic extension with coeval shortening and on the origin of the Alboran Sea together with the surrounding Betic–Rif mountain belts in Morocco and Spain [18,19]. This orocline developed during convergence between Africa and Iberia in late Mesozoic to Tertiary times. Tectonic models that account for its geometry and evolution include: (a) rapid westward motion of a rigid Alboran microplate, (b) subduction zone roll-back and (c) radial extensional collapse caused by rapid convective removal or delamination of lithospheric mantle. Recent tomographic images of the Gibraltar area have clearly visualized the remnants of lithospheric slab structures underneath the Alboran Sea [20]. Paleomagnetic data indicate that large rotations about vertical axis have also taken place, with counter-clockwise rotations in the Rif Mountains and clockwise rotations in the Betic Cordillera [21]. More detailed tomographic images and the exact timing of these tectonic rotations in the Gibraltar arc are still subjects of ongoing studies. In addition, controversy also surrounds the timing of closure and paleogeography of the late Miocene marine passages across the Gibraltar arc [22]. The intramontane basins of the Betics and Rif began to form during the late Miocene, by vertical motions produced by tension perpendicular to compression. This resulted in the development of two marine gateways which were progressively closed during the late Miocene by a complex interplay of both tectonic and glacio-eustatic processes [22,23]. The present-day connection through the Strait of Gibraltar is generally considered to have opened completely at the beginning of the Pliocene [5].

3. Mediterranean paleoclimate records

The theory that (paleo)climate change is dominantly related to perturbations in the Earth’s orbit is at present widely accepted, and astronomical ‘Milankovitch’ cycles are recognized in many sedimentary records of different depositional environments. The Earth’s orbit around the sun is influenced by gravitational interactions with other planets and with the moon. The resulting orbital perturbations give rise to variations in eccentricity, obliquity and precession with main periods of 400 and 100 kyr, 41 kyr, and 23 and 19 kyr, respectively (Fig. 3). These variations in the Earth’s orbit are climatically important because they affect the global, seasonal and latitudinal distribution of incoming solar insolation. They are held responsible for the Pleistocene ice ages but also affect low-latitude climate, such as the African (and Indian) monsoon system. Orbitally forced climatic oscillations are recorded in sedimentary archives through changes in physical, biological and chemical properties. For example, during relatively dry periodsolian dust of Saharan origin (with high Ti/Al ratios, palygorskite and kaolinite) is transported to the Mediterranean,
while during relatively wet periods riverine detrital input (with low Ti/Al ratios, smectite and chlorite) is dominant (Fig. 4). The Mediterranean has the unique advantage that its latitudinal position in combination with its semi-enclosed, landlocked configuration make its sedimentary record particularly sensitive to these astronomically induced oscillations in climate.

### 3.1. Mediterranean astrochronology

The Neogene marine sequences of the Mediterranean provide high-resolution information with regard to the history of climate change and watermass circulation in semi-enclosed marine basins. In the last decennium, the sedimentary cyclicity of these sequences has been used to construct astronomical timescales, which provided a significant breakthrough in the dating of the geological record [6,24,25]. The construction of such timescales involves the calibration of sedimentary cycles or other cyclic variations in sedimentary sequences to computed astronomical time series of past variations in the Earth’s orbit or to derived target curves (Fig. 4). Following the early tuning attempts for the late Pleistocene [26] the astronomical timescale has firmly been established for the last nine million years and now underlies the standard geological timescale for the Pli-Pleistocene [27]. In turn, the paleoclimatic records of the Mediterranean are so exceptionally accurate that they can be used to test the accuracy of the different astronomical solutions for the Earth’s orbital elements [24]. In particular, they shed light upon the changes in the tidal dissipation and dynamical ellipticity of the Earth through time, which may have significant consequences for mantle viscosity models [3]. Moreover, it could be derived from these records that the Pli-Pleistocene ice load has caused an average acceleration in the Earth’s rotation over the past three million years [3].

Today, the Mediterranean astronomical timescale has been extended to 13 Ma based on the marine records which contain the well-known cyclic sapropel sequences [25]. Astronomical tuning revealed that these dark, organic-rich layers correspond to precession minima and insolation maxima, and that they are related to enhanced...
fluvial run-off connected to the intensification of the African monsoon system [28]. Sapropel formation thus corresponds with relatively wet and warm climate phases and, as such, the oxygen isotope record can be used as a guide for correlation purposes. The debate on the exact mechanisms which led to sapropel formation, however, still remains contentious and unresolved [29,30]. Proposed mechanisms include a change to anoxia or an increase of primary productivity as the dominant mechanism, but it may well be that both processes also influence each other. Evidence for higher productivity comes from chemical analyses of productivity proxies [31], while anoxic conditions are indicated by the sedimentary facies, by inorganic geochemical analyses and by isotopic composition of organic matter [32]. Recently, a new variant emerged, suggesting that sapropel formation occurred under oligotrophic conditions in the sea surface and in association with stratified conditions in hydrographic fronts [33].

3.2. Marine–continental correlations

Until recently, the construction of the astronomical timescale was entirely based on these marine sapropel-bearing sequences. For paleoclimate and paleoenvironment reconstructions, however, the inclusion of the continental record would be very helpful since a comprehensive understanding of paleoclimate and paleoclimate change is only achieved by accurate and high-resolution time stratigraphic correlations between the continental and marine record. In fact, the terrestrial sedimentary record seems to be the logical place to look for Milankovitch cycles because, in the absence of oceanographic processes with their intrinsic and complicated non-linear feedback mechanisms, a more direct registration of orbitally induced changes in climate may be expected. A potential serious drawback of using continental successions has been the usual lack of a direct and sufficient time control, also because of the assumed common occurrence of hiatuses which may result from intermittent erosion caused by tectonic activity, base-level changes and autocyclic processes. High-resolution magnetostratigraphic studies on Neogene continental sections, however, show that in several basins regular subsidence was balanced by a continuous sedimentation without major hiatuses [34,35]. In addition, it could be unambiguously demonstrated that the sedimentary cyclicity of these continental successions was also astronomically controlled, resulting in lake-level oscillations caused by periodic changes in climate. For the first time, long continuous records of continental climate proxies (pollen, mammals, etc.) can now be correlated on a precessional bed-to-bed scale (i.e. < 10 kyr) with the time equivalent marine proxy records (oxygen isotopes, sea-surface temperature, etc.). Recent progress in palynology revealed that, apart from high-resolution climate variability, changes in paleoaltitude can also now be semi-quantified [36]. Clearly, this will be extremely helpful in the reconstruction of the paleoclimatic and paleogeographic evolution of the circum-Mediterranean area.

4. Mediterranean–Atlantic connection

The opening and closure of (inter)oceanic gateways is critical in controlling oceanic (paleo)circulation. A prime example is the disruption of the Tethyan Seaway along the African–Eurasian collision zone: closure of the connection to the Indian Ocean likely triggered the middle Miocene climate transition [8], while closure of the Atlantic gateways in the late Miocene resulted in the ‘Mesinian Salinity Crisis’ of the Mediterranean [6]. At present, an anti-estuarine water circulation exists within the Mediterranean (Fig. 5). This circulation pattern is driven by a number of interactive factors, but the most important are the climate and bathymetry of the region [29]. In the present-day situation of the Mediterranean, the loss of water by evaporation is more than double the gain by precipitation and run-off. This inequality drives the circulation across much of the basin and produces an outflow of saline warm water at depth across the sill of Gibraltar and a surface inflow of less saline Atlantic water (Fig. 5). Restricting this outflow would ultimately result in the precipitation of evaporites, which has repeatedly taken place in the strongly restricted circum-Mediterranean basins. Prime examples
are the middle to late Miocene evaporites of the Red Sea basin, the middle Miocene salt deposits of the Carpathian foredeep and the Messinian evaporites of the Mediterranean.

4.1. The Messinian Salinity Crisis

The Messinian Salinity Crisis of the Mediterranean is widely regarded as one of the most dramatic episodes of oceanic change in Neogene history [5,6]. Earliest explanations were that extremely thick evaporites were deposited in a deep and desiccated Mediterranean basin that had been repeatedly isolated from the Atlantic Ocean, but elucidation of the causes of the isolation — whether driven by glacio-eustatic or tectonic processes — had been hampered by the absence of a reliable and accurate time-frame. Recently, however, an astronomically calibrated chronology has been developed for the Mediterranean Messinian based on integrated high-resolution stratigraphy and 'tuning' of sedimentary cycle patterns to the astronomical curves [6]. It showed that the onset of evaporite precipitation, astronomically dated at 5.96 Ma, was remarkably synchronous over the entire Mediterranean basin and that the origin of the Messinian Salinity Crisis was dominantly tectonic, although its exact timing may well have been controlled by the ~ 400 kyr component of the Earth’s eccentricity cycle.

Underlying the Messinian evaporites, cyclically bedded diatomites are generally present in most Mediterranean sequences, suggesting that the diatomaceous facies is an essential part of the lithological sequence associated with basin restriction [37]. Despite intensive studies, the origin of these diatomites remains highly controversial. Partly opposing scenarios explaining cyclic diatomite formation include intensification of Atlantic inflow, periodic upwellings, surface water warming, enhanced fluvial run-off, global sea-level rise and pulsating tectonics. Finally, diatomite deposition may as well be related to the proliferation of diatom species typically adapted to flourish under the low-illuminated waters of the thermocline and nutricline, the phytoplankton referred to as the 'shade flora' [33].

4.2. The Mediterranean–Atlantic gateways

Most paleogeographic reconstructions of the western Mediterranean indicate that the Strait of Gibraltar originated in early Pliocene times. In the late Miocene, however, at least two other con-
connections between the Mediterranean and Atlantic existed: the Betic Corridor through southern Spain and the Rifian Corridor through northern Morocco (Fig. 6b). Based on the sedimentary sequences from the basins in the eastern Betics in Spain, it was claimed that the Betic Corridor closed already somewhere in the Tortonian [22, 38]. Hence, the evaporitic sequences of these basins correspond to a ‘Tortonian salinity crisis’ and are significantly older than the Messinian evaporites of the Mediterranean [37]. In addition, it became evident that at least the southern margin of the Rifian Corridor was emergent from 6.0 Ma onward, while the first mammal exchange between Africa and Europe took place at 6.1 Ma, i.e. earlier than the onset of the Messinian Salinity Crisis [22,23]. At present, the major environmental changes in the Mediterranean cannot yet be compared to tectonic and climatic events in the gateways, although it seems inevitable that the lithological transitions from open marine marls to diatomites and evaporites in the Mediterranean are the result of restriction and/or closure processes in one or both of the gateways. The new Messinian astrochronology can now be used for accurate dating of the sedimentary sequences of the gateway basins. It is especially relevant to know and understand the exact timing and mechanism of closure as well as the paleobathymetric history of the Mediterranean–Atlantic gateways. Current quantitative modelling studies of Mediterranean paleoceanography and resulting depositional environments are critically dependent on such data.

5. Forward to the past

The topography and geography of the Mediterranean area, as we know it today, are perfectly pictured by very accurate satellite images. Even detailed images of the deep mantle structure of the Earth can be obtained from tomographic studies. It is foreseen that ongoing research aiming at an even higher detail of resolution and the increase of new seismic and GPS stations in the circum-Mediterranean area will provide a wealth of new and more accurate data on the ongoing movements of the different structural domains, both in the horizontal and in the vertical plane. This will provide important observations for numerical modelling studies aiming at our physical understanding of the underlying mechanisms. The present-day climate of the Mediterranean area can also be perfectly measured, since very detailed oceanic and atmospheric records are continuously obtained by the numerous weather stations all around the area. Nowadays, significant research effort is directed at the understanding of Holocene climate change, especially in the context of determining the exact contribution of human activity to the increasing global warming related to the greenhouse effect, and the short-term climate

Fig. 6. GIS-based reconstructions by E. van Assen (personal communication, 2002) of the Mediterranean–Atlantic gateway(s) during (a) the late Tortonian and (b) the present-day, after detailed investigations of various paleogeographic reconstructions (altitudes are only schematic).
change on annual to sub-Milankovitch timescales. Oceanic and atmospheric science will benefit substantially from these efforts in the coming years. In addition, a combined research effort in applying current global climate models to archives of past climate (e.g. before the onset of glaciations) will aid in understanding paleoclimate and paleoceanography and in testing the robustness of such climate models, which in turn will help us to better understand the oceanic and atmospheric systems that determine our present climate.

Taking steps back in time, the situation becomes increasingly complicated. The paleogeographic configuration of many areas is still insufficiently known and, consequently, the paleoceanographic processes are difficult to reconstruct. For instance, the most important sills and straits that determined the Mediterranean paleocirculation patterns have continuously been subject to tectonic activity, as both the Gibraltar and Calabrian arc experienced significant vertical and horizontal motions. This was caused by fundamental changes in the configuration of the western Mediterranean subduction zone, but it is very difficult to determine exactly in what stage they were. Moreover, many paleogeographic reconstructions are still subject to controversy, such as the development of the connection to the Paratethys (the former Black Sea) in both time and space. Sea surface temperatures and sea-level fluctuations can be reconstructed from detailed stable isotope curves (δ18O), but changes in humidity and temperatures on land are still uncertain and must be derived from detailed palynological and fossil mammal studies. It is therefore fortunate that a detailed astrochronological framework is available for both the marine and continental realm which allows to correlate and discriminate between the different tectonic and climatic events. Only a multi-disciplinary approach in which all data are reliably tuned into an accurate time-frame will allow a more detailed comprehension of the geodynamic and paleoclimatic evolution of the Mediterranean during its late Neogene evolution. An important step forward will be taken when a series of deep cores is authorized to be drilled through the Messinian evaporites in the various Mediterranean basins, allowing the tuning of all individual evaporite cycles to the astronomical curve and access to the older archives of the deepest Mediterranean basins. This will be possible when the new Japanese ship — with advanced drilling techniques — of the IODP project will visit the Mediterranean during one of its forthcoming campaigns.

If we go further back in time to the middle Miocene, the situation is even more complex. During this interval, several important changes took place, such as the closure of the connection between the Mediterranean and Indian ocean, the expansion of the Antarctic ice cap, massive salt deposits in the former Black Sea area in eastern Europe, and the onset of near modern oceanographic conditions. At present, however, a reliable time-frame is still absent, which makes it very difficult to distinguish between causes and consequences of the various events. Extension of the Mediterranean astronomical timescale is in progress but it will be difficult to stretch it beyond 15 Ma, due to the lack of suitable successions. There is still hope, however, since extra-Mediterranean sequences have enormous potential as well and are currently under investigation [39,40]. In any case, the construction of high-resolution timescales for older ages — whether or not imported from extra-Mediterranean sequences — will remain crucial for extending our knowledge and understanding of the major geodynamic and paleoclimatic processes that took place in the geological past of the ‘Mare Nostrum’ of Earth sciences.

Acknowledgements

I would like to thank Cor Langereis, Charon Duermeijer, Esther van Assen, Frits Hilgen, Luc Lourens and Wim Spakman for their input and stimulating discussions and Judith McKenzie, Rob van der Voo and an anonymous reviewer for their constructive comments.[AH]

References


X. LePichon, J. Angeliier, The Hellenic arc and trench system a key to neotectonic evolution of the Eastern Mediterranean, Tectonophysics 60 (1979) 1–42.


A.E.S. Kemp, R.B. Pearce, I. Koizumi, J. Pike, J. Renne,


Wout Krijgsman is a member of the paleomagnetic laboratory ‘Fort Hoofddijk’ of the Utrecht University, the Netherlands. He has recently acquired an innovation impulse from the Netherlands Organization of Scientific Research (NWO/ALW) on the subject ‘Geodynamics and Climate’. His main research interests are integrated stratigraphic studies of marine and continental sequences, the construction of (astronomical) timescales and, in particular, their application to geodynamic and tectonostratigraphic reconstructions and sedimentary basin analysis.