41 Drop Chapter The Interface Between Tectonic Evolution and Cold-Water Coral Dynamics in the Mediterranean

Rinus Wortel and Paul Meijer

Abstract

Circulation and water properties in the Mediterranean basin, and thus the living conditions for marine biota, including cold-water corals, are a strong function of the connectivity of the basin with neighbouring water masses. The configuration of the basin and its connections with adjacent basins are governed by the interplay of large scale and regional scale geodynamical (or tectonic) processes within the Mediterranean region. As to surface area, it appears that the Mediterranean basin as a whole is closing whereas some of its sub-basins are opening, at the expense of the eastern Mediterranean basin. More important are opening or closure of gateway connections. The pertinent Mediterranean gateways to the Atlantic Ocean and the Black Sea are potentially subject to minor changes resulting from tectonics. However, the impact of such possible changes on marine conditions, including those for cold-water corals, would be slow and of minor magnitude compared to the effects of climate change. Typical aspects of cold-water coral occurrences in the Mediterranean region, notably the uplift and outcrops of Plio-Pleistocene communities and the presence of steep faults (with steered fluid seeps providing nutrients) as preferred production areas, are accounted for by vertical motions in subduction zone evolution.

Keywords

Mediterranean Sea · Cold-water corals · Tectonics · Gateways · Marine conditions

R. Wortel (✉) · P. Meijer
Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands
e-mail: m.j.r.wortel@uu.nl

Introduction

We analyse elements of the geodynamics (or, equivalently: tectonics) of the Mediterranean region envisaged to be relevant to the dynamics of cold-water corals (CWCs) and their habitats. Some tectonic effects appear to be direct geosphere-biosphere connections (in particular, the formation of faults scarps as possible habitats, in combination with fluid seeps providing nutrients), whereas others are indirect, with the geosphere-hydrosphere interactions affecting the circulation and marine conditions of the Mediterranean Sea.

The Mediterranean Sea is a marginal basin to the Atlantic Ocean (e.g., Fusco et al. 2008; Lionello et al. 2012), which implies relevant differences of marine conditions, in particular salinity and temperature, between these two basins. In light of the future evolution of CWC habitats, the principal question to address concerns the nature and stability of the Gibraltar Strait which represents the gateway connection between the two basins, and largely controls water masses interchanges. Thus: Is the Mediterranean Basin opening or closing? Whereas relative motion of the large Eurasian and African plates (a slow convergence) primarily seems to control the future of the Mediterranean Sea, we will argue that tectonic processes within the Mediterranean Basin are likely to be of more importance.

Geodynamics of the Mediterranean Region

Africa-Eurasia Convergence and Continental Collision

As its name indicates, the Mediterranean Sea is surrounded by land, or continents. It acquired this so-called *landlocked basin* configuration as a result of the relative motion of the African and Eurasian plates, which in turn is part of the global pattern of relative plate motions as described in plate

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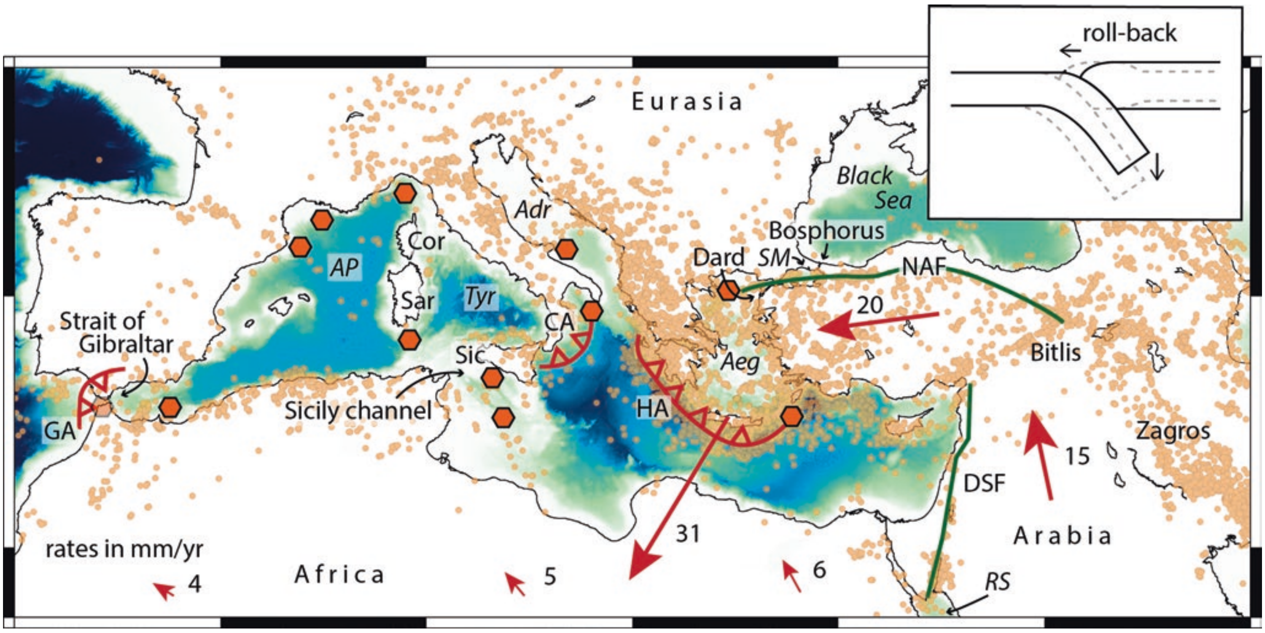

Fig. 41.1 Active tectonics of the Mediterranean. Epicentres of shallow earthquakes (1992–2016, magnitude >4, NEIC catalogue) outline the often diffuse southern boundary of Eurasia. Arrows give motions with respect to Eurasia; rates in mm/year (Reilinger and McClusky, 2011; Nocquet 2012). Discrete faults mentioned in the text are shown in green. Key: *Adr* Adriatic Sea, *Aeg* Aegean Sea, *AP* Alghero-Provençal basin, *CA* Calabrian Arc, *Cor* Corsica, *Dard* Dardanelles, *DSF* Dead Sea Fault, *GA* Gibraltar Arc, *HA* Hellenic Arc, *NAF* North Anatolian Fault, *RS* Red Sea, *Sar* Sardinia, *Sic* Sicily, *SM* Sea of Marmara, *Tyr* Tyrrhenian Sea
Three sites of active or recent subduction (GA, CA, HA) are indicated by the red lines in the main figure. The triangles (dents) along these lines indicate the direction of underthrusting, i.e. the dip direction of the subducted slab (see inset).
Hexagons indicate living occurrences of framework-forming cold-water corals *Lophelia pertusa* and *Madrepora oculata* (compiled from Fink et al. 2015, and Taviani et al. 2017).
Inset: Schematic cross-section of the plate contact region in a subduction zone. In a subduction zone one plate is subducted (underthrust) below another plate. The ocean-floor at the site of downwarping is often marked by a deep-sea trench (which may, however, be filled by sediments). In case of low relative convergence velocities of the plates (less than a few cm/yr) the gravitational forces acting on the cold and, hence, dense subducting plate (“slab”) lead to vertical sinking of the slab (indicated by vertical arrow), from the solid line geometry towards the dashed line geometry. This is accompanied by horizontal motion of the trench or hinge zone at the surface (“roll-back”, indicated by horizontal arrow, also referred to as “trench migration” or “arc migration”), in the direction opposite to that of underthrusting. The lithosphere above the subducted slab and behind the arc adjacent to the plate contact (cf. the Hellenic, Calabrian and Gibraltar Arcs) is extended (“back-arc extension”, towards the dashed line geometry), leading to subsidence of the Earth surface or seafloor. (© Faculty of Geosciences, Utrecht University)

tectonics. The lithosphere is the outer rather strong shell of the Earth, with a thickness characteristically in the order of 100 km. The lithosphere of the Earth is divided in a few tens of large and somewhat smaller units: the “plates”. Since about 80 Ma (i.e., 80 million years ago), the large lithospheric plates Eurasia and Africa, the latter encompassing Arabia until approximately 20 Ma, have been converging in an approximately NNW-SSE direction (Fig. 41.1; see Nocquet 2012 for an overview). The oceanic areas between these continents – collectively referred to as Tethys Oceans – gradually decreased in size through the subduction (see Fig. 41.1, inset) of the Tethys lithosphere in a complex subduction (trench) system along the southern margins of Eurasia.

To first order, the subducted lithosphere was oceanic in nature, i.e. the lithosphere was formed by seafloor spreading, at a spreading centre similar to the present-day Mid-Atlantic Ridge. Relative to oceanic lithosphere, continental lithosphere, in particular its upper crustal part, is made up of different rocks, with a lower average density. This tends to hamper the downward motion of subduction when – after an episode of oceanic lithosphere subduction – continental lithosphere approaches and enters the trench of a subduction zone at the margin of a continent, resulting in *continental collision,* which eventually leaves an imprint in the geological structure in the form of a usually complex mountain belt, the *suture zone.* The continuing motion of Africa and Eurasia led to such a process in the region of present-day southeastern Turkey-northern Iran-Irak (in the Bitlis and Zagros suture zone; Fig. 41.1), in the Oligo-Miocene (from ~30 Ma to ~20 Ma; Okay et al. 2010). This was followed by opening of the Red Sea and formation of the Dead Sea Fault, giving rise to the splitting-off of Arabia from the African plate, to form a new separate plate, the Arabian plate. In terms of the underlying oceanic lithospheric basement, the present-day eastern Mediterranean (east of Sicily) is a remnant of the nearly completely lost Tethys Oceans.

Continental collision does not immediately lead to complete closure of all connections between adjacent marine realms; a moderate-depth or shallow connection may remain open for several million years. In case of the Arabia-Eurasia collision, the closure of the Mediterranean-Indian Ocean gateway, at least as a deep marine connection, was probably completed in the Early Tortonian (Miocene), at about 11 Ma (Hüsing et al. 2009). This left the Mediterranean basin with a (composite) gateway to the Atlantic in the west and with connections to the Paratethys – an assemblage of predominantly shallow seas in central and eastern Europe – to the north of it (e.g., Palcu et al. 2015). Of the latter connections, the one to the Black Sea, through the Dardanelles/Sea of Marmara/Bosphorus (Fig. 41.1), is the only one existing at present.

Internal Mediterranean Tectonics

After continental collision between Africa/Arabia and Eurasia in the Oligo-Miocene, the convergence velocity of the two plates decreased by approximately 50%, to the current low values indicated in Fig. 41.1. In that situation, the downward directed gravitational forces acting on the subducted slabs along the northern boundary of the African plate led to roll-back (see Fig. 41.1, inset), the oceanward migration of the subduction zones and their trench systems (Jolivet and Faccenna 2000; Wortel and Spakman 2000). In the western-central Mediterranean the trench migration was in a SE (later E-SE) direction, in the direction of the present-day Calabrian Arc, and also in W direction towards the present-day Gibraltar region (Fig. 41.1). It gave rise to the motion of Corsica, Sardinia and the Calabrian block away from Iberia and (present-day) southern France, from about 30 Ma onward. In the wake of the migrating slab segments, back-arc extension occurred (Fig. 41.1, inset), resulting in subsidence (with velocities of less than 1 mm/year, but nevertheless producing a total subsidence of 1 km or more over a period of a few million years), the formation of oceanic lithosphere and the corresponding opening of the Algero-Provençal basin between Iberia/Southern France and Corsica-Sardinia (which stopped in the Langhian, about 15 Ma) and later the Tyrrhenian Sea. The back-arc extension process in the western Mediterranean is essentially identical, albeit of a smaller spatial scale, to the process of opening by seafloor spreading of a large oceanic basin such as the Atlantic Ocean. The continental margins created by such extensional tectonic processes (seafloor spreading, rifting, back-arc extension) are named *passive continental margins* (active/passive used in the sense of "with/without subduction zones and related geodynamic activity"). Their usual expression is that of a faulted slope with variable gradient, from the coastal region to the deep parts of the basin, possibly with canyon-type of features.

After considerable activity in the Neogene, with (horizontal) velocities of up to ~ 6 cm/year (Faccenna et al. 2001), arc migration and back-arc extension in the central Mediterranean virtually came to an end at ~0.8–0.5 Ma (Goes et al. 2004); the current (GPS) motion of the Calabrian Arc, the last active segment in this region, relative to stable Eurasia is less than 5 mm/year in a NNE direction (Nocquet 2012).

Gutscher et al. (2012) have explored the recent tectonic activity of the Gibraltar Arc region, in the westernmost Mediterranean; they concluded that very slow, ongoing subduction most likely is the underlying process. Also, GPS data testify to the active motion (~5–6 mm/year, relative to Iberia and Africa) of the arc region (Nocquet 2012). The Strait of Gibraltar gateway has known stages with a distinctly restricted connectivity, which gave rise to the Messinian Salinity Crisis (Flecker et al. 2015; Freiwald, this volume).

This "internal" roll-back process in the western-central Mediterranean thus developed into a final stage in which only two relatively narrow slab segments, the east dipping Gibraltar arc segment and the WNW dipping Calabrian arc segment (Fig. 41.1), continued to migrate to the west and east-southeast, respectively (Jolivet and Faccenna 2000; Wortel and Spakman 2000; Spakman and Wortel 2004). Of these two, the Gibraltar segment is particularly relevant for assessing future developments in the circulation and marine conditions of the Mediterranean, since it plays a key role in shaping the gateway to the Atlantic Ocean.

The currently most active trench migration in the region occurs in the eastern Mediterranean, along the Hellenic Arc (Fig. 41.1), at a velocity of about 30 mm/year. It is accompanied by back-arc extension in the Aegean Sea, which, as yet, has not reached the stage of oceanic lithosphere formation.

Influence of Tectonics on Cold-Water Corals

Direct Effects: Vertical Motions of the Ocean-Floor and the Formation of Fault Scarps

Two kinematic aspects of the subduction zone evolution in the Calabrian, Gibraltar and Hellenic Arcs are directly relevant to the past and modern habitats of CWCs in the Mediterranean and to understanding that they are even exposed on outcrops, a truly remarkable feature in the Mediterranean region (Taviani et al. 2005; Roberts et al. 2009, pp 190–191):

(i) At the lateral edges of the migrating slab segments, the roll-back process in the Mediterranean was accompanied by near-vertical faulting (tearing) of the lithosphere (Govers and Wortel 2005) in the Gibraltar area, a significant part of the coastal regions in the central Mediterranean (Tyrrhenian Sea-Sicily-Calabrian arc; Polonia et al. 2016), and in the eastern part of the Hellenic Arc (Özbakir et al. 2013). Probably even the rifting in the Sicily Channel (Fig. 41.1) is caused by the roll-back-process, in this case of the slab in the Calabrian arc (Argnani 2009). We propose that – as a direct effect of tectonics – this may have produced the steeply inclined fault scarps, steep bathymetry gradients and (hard) substrates, apparently favourable as (although not necessary for) CWC growth habitats (Titschack and Freiwald 2005; Titschack et al. 2005; Roberts et al. 2009; Titschack, this volume). Primary productivity being another governing factor crucial for CWC distribution, the interplay between complex seafloor bathymetry and water masses in highly productive areas promotes suitable environmental conditions for CWC habitats (e.g., White et al. 2005; Mienis et al. 2007; Tracey et al. 2011).

(ii) The subduction zone background of the arcs implies that – even in case the horizontal convergence velocities are very low (<10 mm/year) – vertical motions in the arc region are possible, resulting from the evolution of the subducted slab (Govers 2009). From the well-studied Calabrian Arc, it is known that uplift rates may reach values of about 1 mm/year, with maxima of ~ 2.5 mm/year (Antonioli et al. 2006; Faccenna et al. 2011). Such motions are neither an expression of postglacial rebound nor of regional compression or collision (see Taviani et al. 2005); instead they are considered to be intrinsic elements of the subduction process in a transient, terminal stage of activity, possibly including flow of mantle material around slab edges (Faccenna et al. 2011) and breaking-off and sinking of the deep part of a subducting slab (Fig. 41.1, inset; Wortel and Spakman 2000).

The time scale at which Mediterranean CWCs are analysed, determines the perception of the impact of such vertical motions. Also, the time scale of interest for future activity may well differ from that for past activity. Whereas a 1 mm/year uplift rate during a period of 1–2 million years in recent geological history, resulting in a 1–2 km uplift, adequately accounts for the remarkable outcrops of Plio-Pleistocene CWCs in the NE Sicily-Calabria region (Di Geronimo et al. 2005) and Rhodes (Titschack et al. 2005; Titschack and Freiwald 2005; Titschack, this volume), continuing uplift at the same rate integrated over a significantly shorter future period (say 1000 years) would produce a correspondingly small uplift of only 1 m. At present, finally, any tectonic-rate uplift would incur only a minor effect on water depth because sea level rises at a similar pace (Zerbini et al. 2017).

It should be noted that hard substrates and steep bathymetry are not exclusively caused by tectonic activity in or near subduction zones; similar seafloor conditions can be the result of extensional tectonics accompanied by vertical motions, e.g., in rift zones and along the slopes of continental margins. This is evidenced in many CWC occurrences in the Atlantic realm (e.g., Freiwald and Roberts 2005; Roberts et al. 2009) and – to a lesser extent – also in the Mediterranean (see Fig. 41.1), along the Spanish and French margins in the N-NW part of the western Mediterranean, in the rift zone of the Sicily Channel, off the South coast of Sardinia, and probably also in the Adriatic Sea and the northern Aegean Sea (e.g., Taviani et al. 2017, this volume).

The above effects of tectonics on CWC dynamics are direct not only in a causal sense, but also spatially. They are localised at or near places where tectonic processes occur(red), and their spatial scale is local to regional. With respect to differences and similarities in CWC habitats between the Atlantic Ocean and the Mediterranean Sea, we note that extensional tectonic processes inherent to the formation of passive continental margins (see Sect. *Internal Mediterranean Tectonics*) have been extremely prominent in the Atlantic Ocean (passive continental margins are often termed "Atlantic margins") where they form elongated belts, parallel to the strike of the continental margins. These are readily identified in the distribution of CWC occurrences in the Atlantic Ocean (Roberts et al. 2009, pp 28–29, their Figs. 2.3 and 2.5). In the smaller and more variable setting of the Mediterranean basin the passive margins are of more restricted dimensions, and less dominant. Hence, in the CWC distribution in the Mediterranean both passive margins and subduction zones (at active margins) play a role and, jointly, contribute to a more irregular distribution pattern than in the Atlantic Ocean, even including surface exposure.

Indirect Effects: The Control of Tectonics on Marine Conditions

A widespread, basin-scale influence due to tectonics is possible through tectonic control on the shape of the gateways. This represents an indirect effect of tectonics on CWCs: Changes in gateway depth and width may critically affect the connectivity between the basins involved and potentially result in changes in the temperature, salinity, nutrient availability and ventilation which are all thought to impact on CWC development (Freiwald and Roberts 2005; Alvarez-Perez et al. 2005; Roberts et al. 2006; Fink et al. 2012, 2015; see Smith et al. (2000) for a relationship proposed to use CWC properties to infer paleotemperatures). The literature on the role of gateways is vast; in the context of the past circulation of the Mediterranean, see e.g. Rogerson et al. (2010, 2012), Meijer (2012), Simon and Meijer (2015), de la Vara et al. (2015), de la Vara and Meijer (2016); for the present-day Mediterranean, see also Hayes et al. (this volume) and references therein. For the earlier Paratethys evolution this is a subject of active research (Palcu et al. 2015), aiming at unravelling the Middle Miocene extinction of marine species in the central Paratethys (the eastern part, present-day Romania). This prompts the question: Is the present gateway configuration stable? To answer this question, we briefly explore the stability of the gateways (once) connecting the Mediterranean Sea to the outside, in particular the now closed one in the east (Bitlis), and the only now existing gateway connection with the Paratethys, the Dardanelles/Sea of Marmara/Bosphorus gateway, or briefly, the Bosphorus (Fig. 41.1). In the previous section, we already reviewed the subduction zone background of the Gibraltar Arc and the corresponding open gateway to the Atlantic, the Strait of Gibraltar, including its current horizontal and possible vertical motions.

Eastern Gateway (Bitlis) Continental collision hampers subduction but does not necessarily terminate it. If the forces driving the converging plates can overcome the increased resistance, subduction continues albeit at an often significantly reduced rate. This appears to be the case for the Africa-Eurasia motion: for the Bitlis suture zone, along the Arabia-Eurasia plate boundary high resolution GPS measurements indicate a 15–20 mm/year motion of Arabia relative to Eurasia, in NNW direction (Reilinger and McClusky 2011). Thus, in this region the former gateway to the Indian Ocean is firmly closed and continuing plate motion will maintain this condition.

Bosphorus In contrast with the Gibraltar gateway, the Bosphorus gateway to the Black Sea is not associated with a retreating slab segment in a subduction zone (roll-back). It is, however, located near the active North Anatolian Fault (NAF) and its extensions into the Sea of Marmara (Fig. 41.1). Oktay et al. (2002) proposed that the present Bosphorus connection resulted from the propagation of the NAF into the Sea of Marmara region; new rupturing of the right-lateral NAF in the Sea of Marmara region, with clockwise rotations of the two blocks on each side of the Bosphorus, was accompanied by left-lateral NNE trending faults affecting the area of the strait and the structure of the strait itself ("book shelf faulting").

In the past century, seismic activity along the NAF has been very considerable, with a distinct east-to-west migration, approaching the Istanbul area. In the context of possible further westward migration, recent analyses of seismicity and GPS observations led to the identification of a distinct seismic gap (with a length of 30–45 km) in the fault segments in the central and eastern Sea of Marmara (Bohnhoff et al. 2013; Ergintav et al. 2014; Schmittbuhl et al. 2016). The seismic gap is an indication of delayed earthquake activity. The length of the gap and the estimated present slip deficit of ~ 2.5 m are considered to be sufficient to generate a magnitude ~ 7 earthquake. The time scale for possible long-term changes, however, is governed by the long- term (horizontal) relative motion along the North Anatolian Fault (about 23–25 mm/year; Nocquet 2012; Schmittbuhl et al. 2016).

Both the Bosphorus and the Strait of Gibraltar provide the Mediterranean Sea with an outlet for its relatively salty waters and both act as a source ("inlet") of water of lower salinity. Tectonically induced further constriction of these gateways would thus raise Mediterranean average salinity, and vice-versa. The Strait of Gibraltar also affects mean water temperature in that it compensates the loss of heat incurred from the exchange of heat between the sea and the atmosphere. Of the internal processes, perhaps the continuing migration of the Hellenic Arc may entail a small change in the deep circulation, given that the arc accommodates the passage (east and west of Crete) of dense waters formed in the Aegean Sea.

Any tectonically induced change in marine conditions is likely to be slow and best considered a long-term trend (100 kyr to 1 Myr) overprinted by the higher frequency change due to, among others, orbital-induced climate variation (Skliris this volume, discusses the current rise in salinity related to changes in the water cycle). Of course, the very fact that the Mediterranean basin is sensitive to these climatic changes is due to its gateway-controlled landlocked nature and thus, ultimately, a consequence of tectonics.

Conclusions

The ongoing large-scale motion of the Eurasian and African plates drives active and continuing *closing* (i.e., decrease of surface area) of the Mediterranean Sea basin as a whole. Within the Mediterranean basin, arc migration and back-arc extension continue to lead to changing configurations of sub-basins, implying that the basins, notably the Aegean Sea and possibly – to a very minor extent – the Tyrrhenian Sea, are *opening*, i.e. increasing in size, at the expense of the Eastern Mediterranean basin. More importantly than a reduction in surface dimensions of the Mediterranean Sea, tectonic processes may lead to changes in the width and/or depth of the Strait of the Gibraltar and Bosphorus gateways. The impact of such possible changes on marine conditions relevant for CWCs, however, would be slow and of minor magnitude compared to the effects of climate change.

Typical aspects of CWC occurrences in the Mediterranean region, notably the presence of steep fault scarps (as preferred production areas) and the (long-term) uplift and surface exposure of Plio-Pleistocene CWCs, are accounted for by faulting processes and vertical motions characteristic for the terminal stage the Mediterranean subduction zones are in.

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