Straits and seaways: controls, processes and implications in modern and ancient systems

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Abstract: Straits and seaways are connections between basins, key areas for exchange and transfer of water, heat, biota and sediments, and they can influence regional and global climate. A better understanding of strait/seaway dynamics, their evolution and preserved deposits is, therefore, fundamental to reconstructing the palaeoecology, palaeogeography and stratigraphy of interconnected basins. Straits and seaways are also important for understanding climate dynamics in Earth's past, and for safely exploiting energy resources (fossil and renewable). This volume aims at improving the knowledge on this topic, and at providing a comprehensive collection of state-of-the-art works bringing together complementary disciplines. Even though studies on modern and ancient straits and seaways exist, they are not necessarily conceived towards a better geological understanding of these features as depositional systems in their own right. In this introduction, we emphasize the geological importance of straits and seaways, summarizing the content and key findings of the contributions on this topic. The articles included in this volume explore four main research themes related to straits and seaways: (1) occurrence and classification; (2) morphological features, facies and stratigraphic variability, sedimentary processes and dynamics; (3) tectonic and climatic controls, their feedback with climate changes; and (4) palaeogeographical reconstructions and preservation of associated deposits.

Connections between basins are called straits and seaways but these terms are loosely defined, and here we will discuss their definition, variability and importance in introducing the contributions of this special publication. This collection of articles add new information on different aspects of straits and seaways knowledge (Fig. 1) from their classification, processes, palaeogeographical evolution, climate feedback or examples of preserved basin-fill sediments and stratigraphy. The focus is on both modern and ancient examples. The latter formed and demised during the geological past and are interpreted on the basis of their partially preserved deposits. The overarching scope of the book is to shed new light on the importance of straits and seaways in the evolution of the Earth surface and their distinction as 'standalone' depositional basins with particular recognizable characteristics.

What are straits and what are seaways?

Understanding straits and seaways is quintessential for present-day sedimentary depositional systems, for regional geological reconstructions as well as for large-scale and long-term tectonic and palaeogeographical evolution. A strait is defined in the *Glossary of Geology* (Neuendorf *et al.* 2005) as 'a relatively narrow waterway connecting two larger bodies of water' (Fig. 2a). This is a loose definition with no reference to the strait width, length, depth, type of water circulation or duration through geological time (**Rossi *et al.* 2023**). Although the definition captures the essence of these as 'connectors', it lacks information on morphology and geological characteristics. One of the goals of this volume is to provide evidence for the large variability that exists among many modern examples of straits and seaways (**Dalrymple 2022**) and ancient examples described in the

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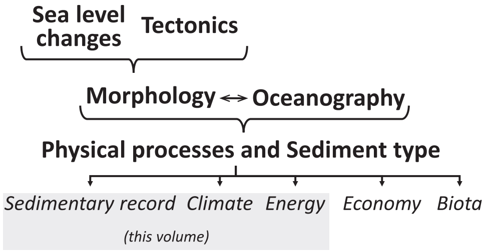

Fig. 1. Controlling factors of straits and seaways and their relevance to society, with the research focus of this volume highlighted.

volume, and to propose a distinctive use of the terms 'straits' and 'seaways' (**Rossi *et al.* 2023**) based on their physical characteristics.

Straits and seaways have multiple origins, morphologies and complex sediment transport processes (Fig. 2b) which result in quite a range of possible sedimentological and stratigraphic architectures. However, regardless of their origin, straits and seaways represent individual depositional basins with sedimentary systems in their own right, characterized by specific sediment dynamics. Therefore, they form characteristic stratigraphies that can be recognizable in the rock record. The 'strait basins'

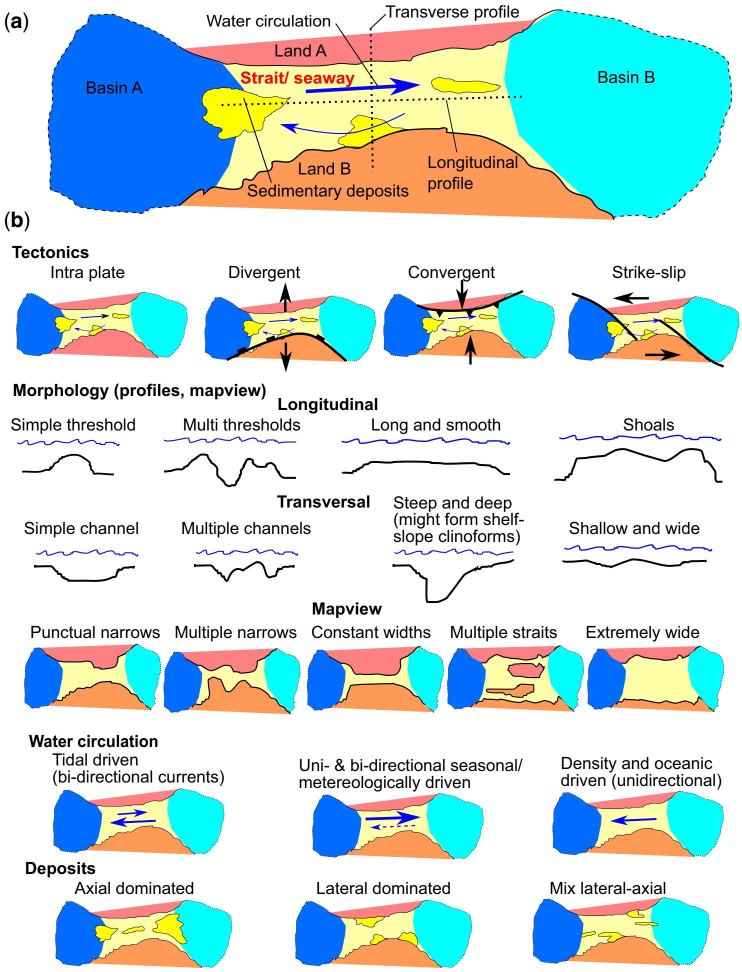

Fig. 2. Variability of straits and seaways. (**a**) Main controls on straits and seaways (tectonics, morphology, water circulation, sedimentary deposits). (**b**) Examples of straits and seaways emphasizing the variability of the main controls influencing dimensions, water circulation, tectonic regimes, sediment sources and accumulation rates. Examples emphasize the extremely large variability and are not intended to be exhaustive and to explore all possible case combinations present in nature.

have a shorter evolution than adjacent basins, to which they connect, and the sedimentation of the strait basin reflects the oceanographic processes that can be dominated by either 'intermittent' (such as tidal or meteorological) or 'persistent' (such as density-driven) oceanic currents (**Dalrymple 2022**). In the case of wider and deeper marine connections, the water circulation and sediment transport are more complex than in narrow straits and it is suggested the strait basins are called seaways (**Rossi *et al.* 2023**).

During their evolution, most sedimentary basins develop narrow connections with adjacent basins, at least during part of their history. Opening and closing of straits and seaways can occur during the initial period of continental rifting and ocean flooding (e.g. the Atlantic rifting), or at the ocean demise when the connection with the main oceanic basin is lost, for example during the closing of the Tethys Ocean (e.g. **Palcu and Krijgsman 2022**), or the rise of the Alpine orogenic front (**Kalifi *et al.* 2022**). Basin connections can be separated as straits or seaways (**Rossi *et al.* 2023**) based on dimensions (width, depth, areas), time of activity and stratigraphic architecture (**Rossi *et al.* 2023**) or on oceanographic processes (**Dalrymple 2022**).

Sedimentary processes variability in straits and seaways and associated deposits

Straits and seaways, the connections between two adjacent basins, have a wide range of dimensions and morphologies (Fig. 2b; **Dalrymple 2022**; **Rossi *et al.* 2023**) and sediments are transported by a multitude of processes (Fig. 3), which result in complex sedimentation patterns and stratigraphies. Eustatic or tectonic processes control long-term morphological (depth/width/length) evolution as well as adjacent sediment sources, and impact straits' and seaways' stratigraphy similarly to other sedimentary basins (Longhitano 2013). However, what is specific to straits and seaways is that sediment transport is more variable along axial (i.e. parallel to the strait/seaway margin) and transverse sources (Fig. 3), and that this can change within one depositional sequence (sedimentary cycle). The sediment sourced through lateral or substrate erosion by marine currents can also be significant in straits and seaways (Fig. 3) and is more common than in other basin types.

Facies models developed so far focus on the axial energy changes from the narrowest constriction of the strait toward the basins to which it connects (Longhitano 2013), or on the strait-margin sediments that are laterally skewed by currents (e.g. Rossi *et al.* 2017), such as deflected deltas, quite common in seaways such as the Western Interior Seaway, with very complex sediment transport paths and facies variability (Longhitano and Steel 2016). Other facies models have been focusing on contour and bottom currents' deposits that can develop at the exit of a strait or seaway (e.g. Hernández-Molina *et al.* 2006; Stow *et al.* 2009, 2013).

Research on straits and seaways sedimentology is a relatively new and exciting frontier. Expanded facies models, therefore, building upon the already existing ones would advance our understanding of these systems further, taking into account all types of water circulation and morphological setting (see for example **Dalrymple 2022**).

Importance of straits and seaways

The distribution of straits and seaways in the present Earth's geography has a strong impact on our society

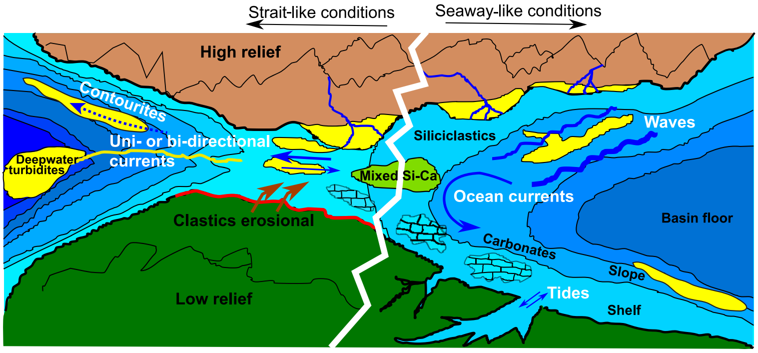

Fig. 3. Possible sedimentary processes and depositional environments of straits and seaways. Note axial currents that deliver sediments to shallow or deep water with clastics being either river-derived or eroded, or carbonate sediment. Towards the right, a wider seaway with complex water circulation, shallow or deep, siliciclastic or carbonate sediments.

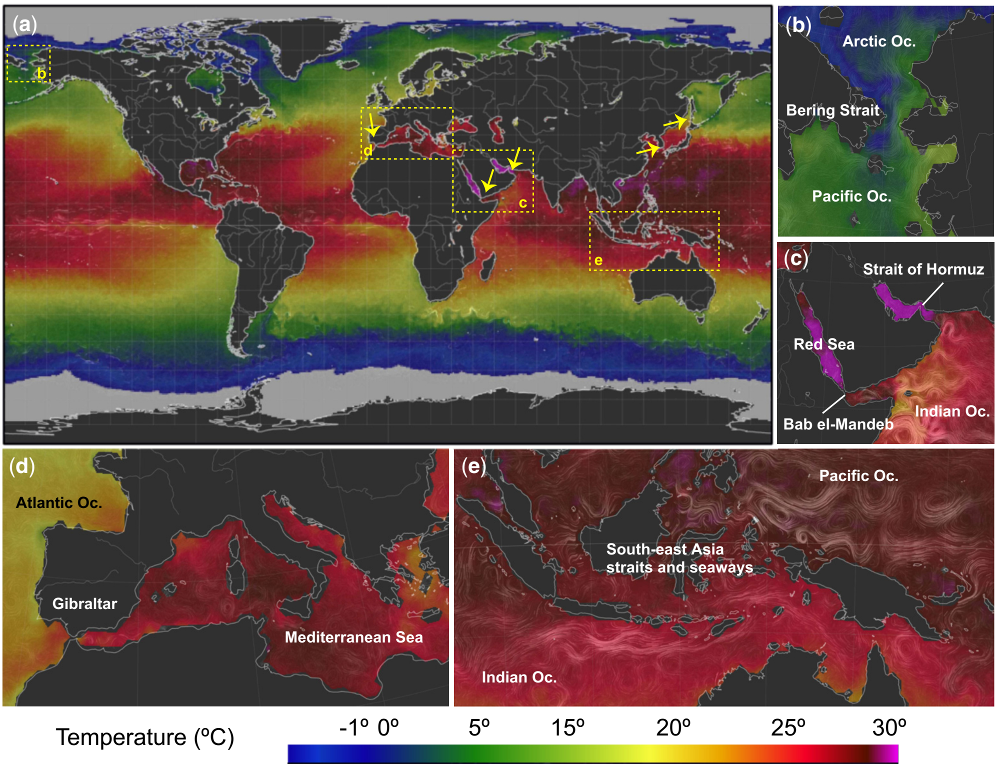

Fig. 4. Importance of modern straits and seaways. (**a**) Global ocean sea-surface temperature distribution and currents (from https://earth.nullschool.net). Note temperature difference of water masses separated by key straits (yellow arrows). (**b–e**) Details of key straits and seaways which exchange water with distinct density and temperature, controlling modern climate and also fauna movements between larger basins: Bering (b), Hormuz and Bab el-Mandeb (c), Mediterranean straits (d) and SE Asia straits and seaways (e).

since it controls trading/shipping routes and local and planetary climate/weather patterns through water circulation and ocean heat exchanges (Fig. 4). Additionally, as straits and seaways influence the connection between basins, their opening and closure through geological time drive the movements and distribution of species in both marine and terrestrial realms (e.g. through the formation of land bridges providing migration routes). Also, straits and seaways of the past can accumulate thick sedimentary deposits that may contain economical resources (e.g. hydrocarbons, water, minerals).

Sedimentary basin evolution

The understanding and reconstruction of straits and seaways is a key component in long-term palaeogeography and basin evolution studies, that requires the use of tectonic and stratigraphical reconstructions, sedimentology, palaeontology and geochemical proxies (e.g. Doré 1991; Akhmetiev and Beniamovski 2009; Flecker *et al.* 2015; Straume *et al.* 2020; **Kalifi *et al.* 2022**; **Palcu and Krijgsman 2022**).

Throughout Earth surface evolution, the migration of tectonic plates created and closed a multitude of straits and seaways during multiple cycles of sea-level change similar to modern times (Fig. 5). For example, the breakup of the supercontinent Pangaea led to the formation of a series of seaways and straits (e.g. Ford and Golonka 2003; Dera *et al.* 2015), such as the proto North Atlantic Seaway (or Laurasian Seaway) and the Hispanic Corridor (e.g. Doré 1991; Porter *et al.* 2013).

However, understanding the characteristics of the palaeo-straits and -seaways beyond their mere location, such as dimensions (width, depth) and water exchanges (current strengths, volumes, densities and temperatures), requires the use of a multidisciplinary approach, which can add details to their reconstruction.

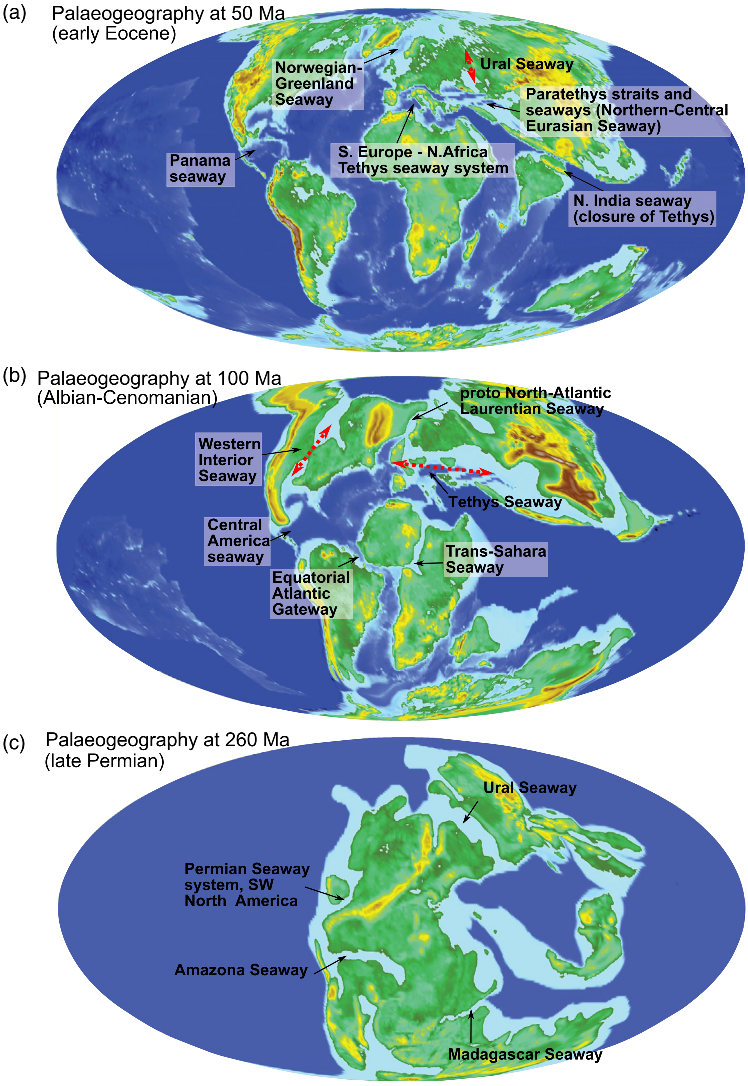

Fig. 5. Palaeogeographical reconstructions of the plate configuration on Earth with the indication of some of the most important straits and seaways of the past. (**a**) Early Eocene (50 Ma). (**b**) Albian–Cenomanian (100 Ma). (**c**) Late Permian (260 Ma) (grids from Scotese and Wright (2018), PALEOMAP Paleodigital Elevation Models (PaleoDEMS) for the Phanerozoic).

Besides plate movements and tectonic activity, sea-level oscillations are also a key factor that control strait and seaway evolution. If straits and seaways are shallow compared to the amplitude of sea-level changes, they could become subaerially exposed during periods of sea-level lowstands (Figs 6 & 7, see also **Dalrymple 2022**), especially during high-amplitude sea-level perturbations, such as icehouse periods like the Paleozoic or from the Miocene to the present (see Fig. 7e for last 5 Ma).

Marine geologists have extensively studied continental shelf evolution since the Last Glacial Maximum (LGM), highlighting the interplay between sea-level changes, seafloor morphology and hydrodynamics. For example, a recent study of the Jeju Strait shelf (Korea) clearly shows depositional environment evolution from subaerial exposure and fluvial deposits (i.e. no strait, see also Fig. 7d), to flooding and transgressive reworking of previously deposited sediments, to highstand mud deposition

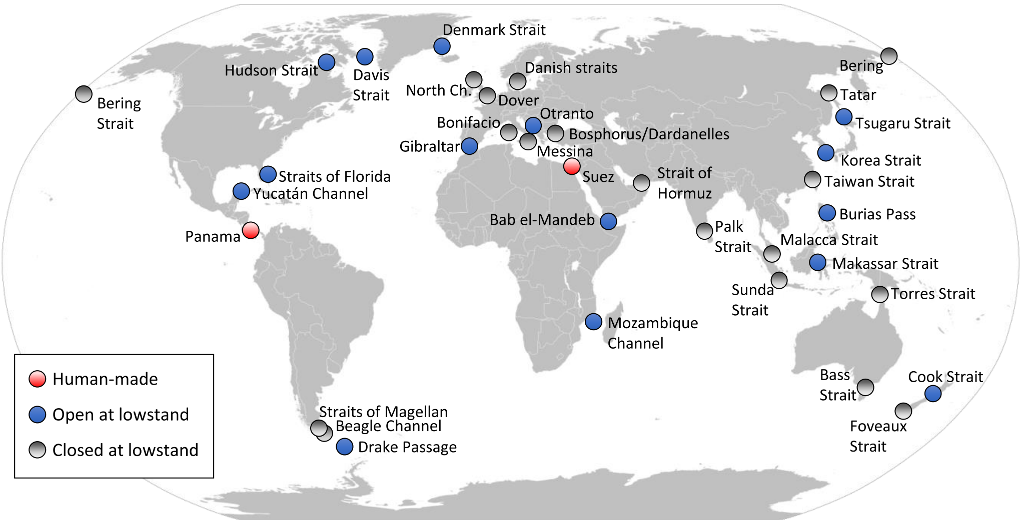

Fig. 6. Location of the main straits and seaways in the world, with an indication of their closure during Late Pleistocene sea-level lowstands.

in a strait environment (Lee *et al.* 2022). A similar evolution occurred in the Dover Strait, where, during the LGM (Fig. 7c), the Axial Channel and Channel river were flowing through the Dover gorge (Hijma *et al.* 2012). During Paratethys closure the Dacian Basin was repeatedly connected through straits by adjacent Black Sea and Pannonian basins during the upper Miocene, and depositional systems alternated between lacustrine and fluvial (Jipa and Olariu 2009, 2013; Krezsek and Olariu 2021). During the Eocene, Oligocene and part of the Miocene, a larger area of the Paratethys was crossed by straits (see also **Palcu and Krijgsman 2022**).

Economy and geopolitics

Modern marine connections are geopolitical and commercial strategic elements, as they force shipping and trading routes through a constriction that represent maritime choke points (Fig. 8; see also Dobson *et al.* 2020). A survey of the ship cargo routes shows that straits are the busiest shipping routes either natural (e.g. the English Channel, the Strait of Malacca, Bosphorus and Dardanelles Strait, Strait of Hormuz), or artificial canals that cut isthmuses (Panama and Suez canals, Figs 6 & 8). These global chokepoints have thus been called ‘the strategic straits’ by Caracciolo (2019).

Climate: oceanography and heat transfer

The importance of straits and seaways in regulating climate equilibria stems from their influence on ocean circulation (e.g. Berggren 1982; Zachos *et al.* 2001; Vahlenkamp *et al.* 2018). Oceans are the main driver of the global climate system, and oceanic heat transport has changed through geological times as a consequence of plate movements and the creation of connections (straits, seaways) or barriers between oceans (Berggren 1982).

The location and bathymetry of straits and seaways (see Figs 4 and 5 for some examples) are therefore considered to be two of the critical elements that control global climate dynamics, together with continental topography and concentrations of greenhouse gases (Berggren 1982; Zachos *et al.* 2001). Therefore, the understanding of marine connections is very important to fully explain and reconstruct Earth climate history and evolution, also in the light of current climate changes.

For example, great attention has been devoted to the study of climate changes (e.g. onset of global cooling) and straits–seaways configuration during the Cenozoic (e.g. Berggren 1982; Zachos *et al.* 2001; Vahlenkamp *et al.* 2018; Straume *et al.* 2020; see also **Bahr *et al.* 2022**; **Palcu and Krijgsman 2022**). Even though uncertainties remain, especially regarding precise timing of straits and seaways opening/closure or dimensions, there is general agreement on their importance to global or local climatic changes. The opening of the Drake and the Tasmanian passages is considered to be one of the main triggers for the appearance of the first Antarctic ice sheets in the Oligocene, while, with more uncertainties, the closure or shallowing of the Central American Seaway is thought to have strengthened the Atlantic Meridional Overturning Circulation

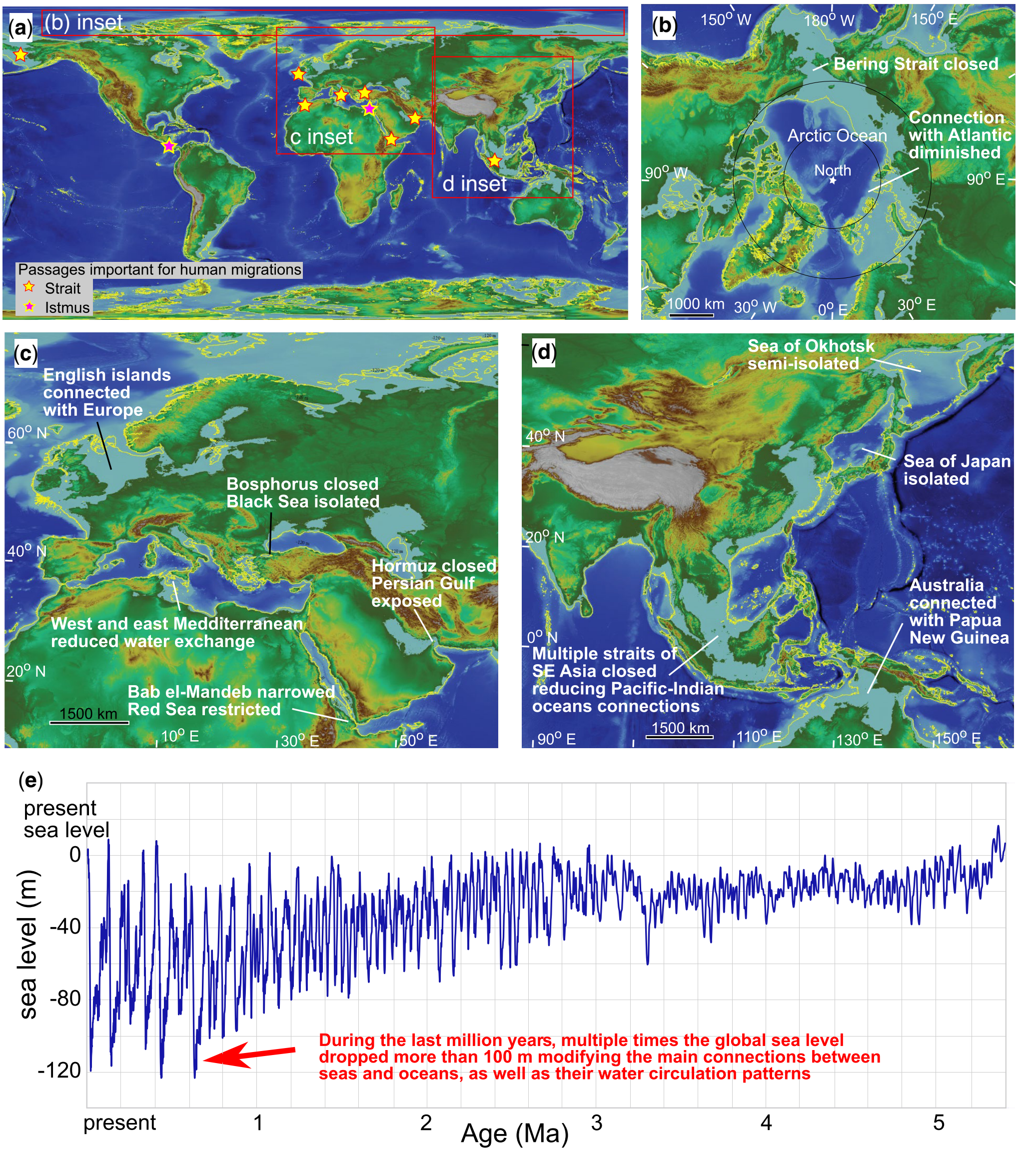

Fig. 7. Straits and seaways subaerially exposed during sea-level lowstand. Yellow lines on all images indicate the −120 m depth, an approximation of the mean lowstand elevation in the past 800 000 years. (**a**) Global view with location of land–sea passageways important for human migration pathways. (**b**) Arctic Ocean detail. (**c**) Geographical effects of the sea-level lowstand changes in Europe, and (**d**) Asia. (**e**) Sea-level curve reconstructed for last 5 Ma. Source: data for (e) from Miller *et al.* (2005).

(e.g. Berggren 1982; Zachos *et al.* 2001; Karas *et al.* 2017; Vahlenkamp *et al.* 2018; Straume *et al.* 2020; see also **Bahr *et al.* 2022**). The relationship between straits–seaways configuration and climate is more challenging the further back in time we go, but studies exist on this topic also for Mesozoic seaways, proving their fundamental role in regulating climate equilibria throughout Earth's history (e.g. Dera *et al.* 2015; Korte *et al.* 2015).

The task of unravelling the feedback between ocean circulation, seaway and strait configuration, and climate is challenging, and a multidisciplinary approach is needed, including but not limited to, plate configuration and tectonic reconstructions,

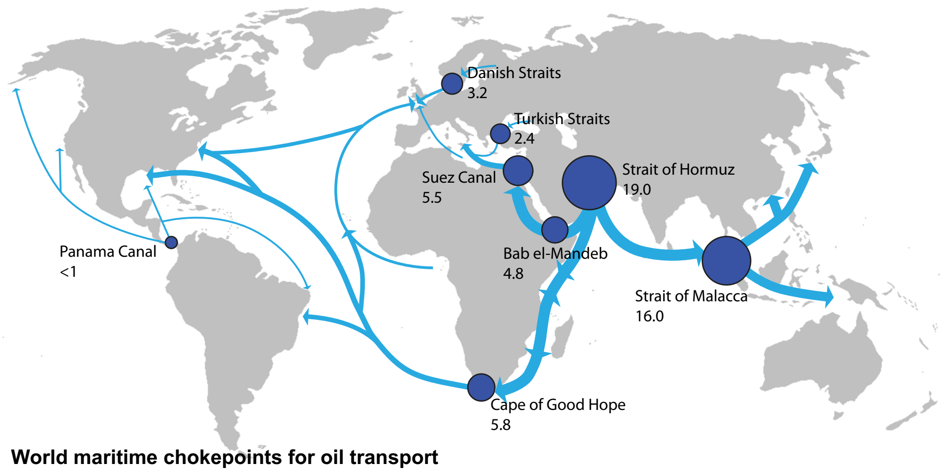

Fig. 8. Importance of modern straits and seaways. Trading shipping routes (light blue) represent arteries of the modern economy and exchange of conventional energy resources. Circles indicate millions of oil barrels transiting per day (2016 data). Source: US Energy Information Administration (2017).

geochemical proxies for ocean circulation (e.g. Nd isotopes), palaeo-temperatures, ocean productivity, global carbon cycle perturbations (δ^{18}O and δ^{13}C), climate and ocean circulation models, stratigraphic correlations, palaeontological analyses and palaeoenvironmental and sedimentological studies (e.g. Zachos *et al.* 2001; Hernández-Molina *et al.* 2014; Dera *et al.* 2015; Flecker *et al.* 2015; Karas *et al.* 2017; Vahlenkamp *et al.* 2018).

Energy: hydrocarbons and renewable energy

One of the most outstanding features of current-dominated straits and seaways is the occurrence of units of orderly stacked cross-beds, tens to hundreds of metres thick, as seen in many ancient examples (e.g. Longhitano *et al.* 2012, 2021; Rossi *et al.* 2017; Archer *et al.* 2019; Telesca *et al.* 2020). These successions form prolific hydrocarbon reservoirs in the subsurface, such as the middle Jurassic Garn Formation in the subsurface of the Norwegian Continental Shelf (Messina *et al.* 2014), among many others. The Laurasian Jurassic Seaway is a good example where several clastic wedges prograded into the seaway, forming regressive–transgressive tongues that now constitute oil and gas fields, and are also being evaluated as potential storage sites for CO_2 (Patruno *et al.* 2015; Ringrose 2018; Lothe *et al.* 2019; **Folkestad and Steel 2022**). Understanding strait or seaway palaeogeography, stratigraphy and sedimentary variability is therefore a key first step in predicting the type or occurrence of source rocks, reservoirs and seals (e.g. Bjerrum *et al.* 2001).

Modern straits and seaways also have potential to produce renewable energy. Due to flow constriction within straits, currents tend to be accelerated. For this reason, straits are becoming increasingly attractive as potential sites for installing tidal stream turbines, as part of the international effort to reduce greenhouse gas emissions (e.g. Chong and Lam 2013; Calero Quesada *et al.* 2014; Evans *et al.* 2015). However, current velocities are not the only important parameter to consider when assessing the feasibility of turbine instalment. Spatial and temporal variability of currents, occurrence of high frequency internal waves and tidally-driven flow reversals (considered as undesirable), seismic hazard assessment (as straits are often located in geologically active areas) and migration of bedforms at the seafloor also need to be characterized in order to find suitable areas to produce energy (Calero Quesada *et al.* 2014; Evans *et al.* 2015).

Biota: chokepoints, hotspots and land bridges

Straits and seaways are often a hotspot of biodiversity, as their typical hydrodynamics allow the presence of a greater variety of marine organisms and high specific diversity. For example, intense and alternating currents coupled with upwelling (bringing lower temperatures and high concentrations of nitrogen and phosphorus) are the basis for the development of communities (pelagic and coastal benthic) of extreme ecological interest. Examples of this biodiversity are the presence in the Strait of Messina of some Atlantic species, such as the laminaria (large brown algae *Sacchoryza polyschides*, *Laminaria ochroleuca*) which can form well-structured subsea forests. The Strait of Gibraltar also boasts an extraordinary richness in terms of natural biodiversity. It is no coincidence that an ‘Intercontinental Reserve of the Mediterranean Biosphere’ of over 900 000 ha has been established on both sides of the Gibraltar Strait, in Morocco and Spain. Straits are also very important migratory routes for large pelagic fishes and cetaceans. Consequently, there is an inherent environmental risk, related to overfishing and intense cargo traffic, which can cause pollution, habitat quality deterioration and extinction of the more sensitive marine species.

Additionally, the opening or closure of straits and seaways has a direct influence on the exchange and migration of biota between different basins (or land masses if land bridges are formed), or on the occurrence of biotic diversification and endemism (e.g. Akhmetiev and Beniamovski 2009; Brikiatis 2016). For example, the final closure of the Central American Seaway, dated at *c.* 2.7 Ma, is thought to have allowed the biotic interchange between North and South America (Straume *et al.* 2020 and references therein) whilst the Beringia land bridge is thought to have acted as a dispersal route since the Cretaceous (Graham 2018).

In the Pleistocene, glacio-eustatic fluctuations (Bintanja *et al.* 2005) triggered high-frequency connection/disconnection among land masses (Figs 6 & 7), deeply affecting the migration of fauna (Esselstyn and Brown 2009; Adeleye *et al.* 2021) and possibly humans (Fernandes *et al.* 2006).

During the LGM, many of the modern straits (e.g. Strait of Malacca or the Strait of Hormuz) were exposed land (being part of the so called ‘Aquaterra’, *sensu* Dobson 2014; Figs 6 & 7), impacting migration of human populations (Dobson *et al.* 2020). For example, it is very likely that the first humans crossing to America from NE Asia moved along the coastline and archipelagos of the exposed Bering Sea (Dobson *et al.* 2020, 2021; Fig. 7b) and that the colonization of Sicily occurred later than in the rest of the Italian peninsula, due to the timing of the closing of the Messina Strait, allowing a land bridge to form (Antonioli *et al.* 2016).

Current volume

This collection of 17 articles covers studies on modern and ancient straits and seaways located in many different geographical and geological areas of the globe (Fig. 9) and includes documentation of small and large straits/seaways dominated by a range of processes and from different geological epochs.

The papers included in the current volume provide an excellent overview of state-of-the-art knowledge of modern (**Andreucci *et al.* 2022**; **Çağatay *et al.* 2022**; **Dalrymple 2022**; **Deiana *et al.* 2022**; **Martorelli *et al.* 2022**) and ancient (**Bahr *et al.* 2022**; **Beelen *et al.* 2022**; **Caterina *et al.* 2022**; **Cavazza and Longhitano 2022**; **Dorsey *et al.* 2022**; **Folkestad and Steel 2022**; **Kalifi *et al.* 2022**; **Kang *et al.* 2022**; **Minor *et al.* 2022**; **Palcu and Krijgsman 2022**; **Puga-Bernabéu *et al.* 2022**; **Rossi *et al.* 2023**) straits and seaways, and their importance for palaeogeographical and palaeoenvironmental reconstructions, reservoir characterization and impact on global climate. These papers focus on: (1) the occurrence and classification of straits and seaways (**Dalrymple 2022**; **Rossi *et al.* 2023**); (2) sedimentary processes and dynamics, facies, facies architecture and stratigraphic variability (**Andreucci *et al.* 2022**; **Beelen *et al.* 2022**; **Çağatay *et al.* 2022**; **Caterina *et al.* 2022**; **Dalrymple 2022**; **Deiana *et al.* 2022**; **Folkestad and Steel 2022**; **Kang *et al.* 2022**; **Martorelli *et al.* 2022**; **Minor *et al.* 2022**; **Puga-Bernabéu *et al.* 2022**); (3) tectonic and climatic controls on the evolution of straits and seaways (**Cavazza and Longhitano 2022**; **Dorsey *et al.* 2022**); and (4) their feedback with climate changes, paleogeographical reconstructions and preservation of associated deposits (**Bahr *et al.* 2022**; **Kalifi *et al.* 2022**; **Palcu and Krijgsman 2022**).

Dalrymple (2022) provides a comprehensive review of the morphology, physical oceanography and facies of modern straits and seaways. This work highlights the extreme complexity and variability of modern passageways, providing an overview of the geometry and geological origin, their main physical processes, and sedimentary deposits filling shallow- and deep-water case studies. The physical processes operating within straits are important, because they determine the nature of the deposits. The author highlights how, besides tidal currents, meteorological, oceanic and density-driven currents are also frequently occurring processes, albeit difficult to recognize in the geological record. Additionally, the author shows how siliciclastic-dominated strait deposits can fit within a sequence stratigraphic context, forming during transgressive system tracts and expected to overlie estuarine deposits, and provides a model to predict when the fastest currents can occur within a strait.

Rossi *et al.* (2023) review the geomorphological, oceanographic, geological and depositional characteristics of straits and seaways based on well-documented modern and ancient case studies, with the purpose of improving our understanding of these features and to better address the geological use of the two terms. The authors find that ‘strait’ and ‘seaway’ could be differentiated by their scale, both spatial and temporal. This spatial–temporal dichotomy influences the type and persistence of the dominant oceanographic circulation and sediment distribution. Therefore, their stratigraphic

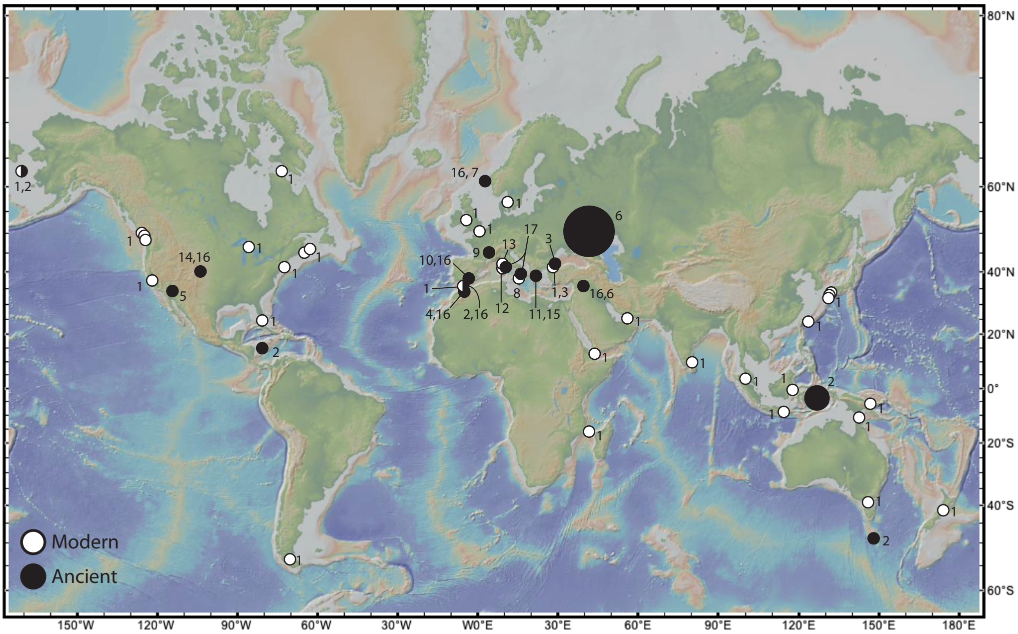

Fig. 9. Location of modern and ancient examples of straits and seaways documented in the articles of this volume. Some papers report data on multiple straits/seaways and are represented by larger circles such as Paratethys or Indonesian areas. Numbers refer to papers and are hyperlinked in the online version: 1, Dalrymple (2022); 2, Bahr *et al.* (2022); 3, Çağatay *et al.* (2022); 4, Beelen *et al.* (2022); 5, Dorsey *et al.* (2022); 6, Palcu and Krijgsman (2022); 7, Folkestad and Steel (2022); 8, Martorelli *et al.* (2022); 9, Kalifi *et al.* (2022); 10, Puga-Bernabéu *et al.* (2022); 11, Caterina *et al.* (2022); 12, Andreucci *et al.* (2022); 13, Deiana *et al.* (2022); 14, Minor *et al.* (2022); 15, Kang *et al.* (2022); 16, Rossi *et al.* (2023); 17, Cavazza and Longhitano (2022). Figure made with GeoMapApp (http://www.geomapapp.org)/CC BY/CC BY (Ryan *et al.* 2009).

signature in the rock record is expected to be significantly different. **Rossi *et al.* (2023)** conclude that straits and seaways are end members of a continuum between the two sets of passages that can occur both in time and space, giving rise to the occurrence of intermediate cases, with characteristics that are transitional between the two end members.

Bahr *et al.* (2022) and **Palcu and Krijgsman (2022)** show the link between strait and seaway dynamics and global climate. **Palcu and Krijgsman (2022)** focus on the straits of the Paratethys, reviewing their connectivity changes from the Eocene to the Oligocene–early Miocene. The authors explore the link between strait closure, anoxia development in isolated or semi-isolated basins of the Paratethys and consequent carbon storage, and the transition from Eocene greenhouse to Oligocene icehouse conditions.

Bahr *et al.* (2022) offer a review of five major Cenozoic gateways (Tasmanian Gateway, Strait of Gibraltar, Central American Seaway, Indonesian Throughflow and Bering Strait), whose opening or closure had an impact on global ocean circulation and climate (e.g. the build-up of northern and southern hemisphere ice sheets). The authors stress the importance that even small-scale changes in gateway configuration can impact global ocean currents and climate in a strongly non-linear way.

Andreucci *et al.* (2022), **Martorelli *et al.* (2022)**, **Deiana *et al.* (2022)** and **Çağatay *et al.* (2022)** offer a review of modern Mediterranean straits. **Andreucci *et al.* (2022)** document an example of the modern Asinelli Strait, NW Sardinia, which forms a very shallow water passage between mainland Sardinia and Pianosa Island. The study focuses on the dynamics of bioclastic or mixed bioclastic–siliciclastic sandy bedforms, ranging from ripples to sand waves to sand dunes and sandy cusps. The bedforms move under the effect of wind-driven currents and their zoning and characters are controlled by the morphology of the strait and distance from the sill. It is an example of a water passage where the effect of wind (seasonally and randomly varying) prevails on other oceanographic or tidal processes. Seagrass meadows are also present, possibly feeding the carbonate fraction of the sedimentary system.

Deiana *et al.* (2022) analyse the Bonifacio Strait between Corsica and Sardinia. The available dataset includes reflection seismics, grains size, multibeam and side-scan sonar. The sill depth is 70 m below sea-level, the regime is microtidal and the strait morphology rather complex, as the sill emerged and was eroded during glacio-eustatic lowstands. The study focuses on variability and distribution of bedforms (sand patches, ribbons, 2D and 3D dunes). Some dune fields were active for more than ten years and the direction of bedform migration is somewhat different with respect to the prevailing direction of winds and modelled bottom current. This fact offers interesting hints on the possible fate of pollutants in case of an accidental spilling, a subject that is relevant for this environmentally sensible and nautically dangerous strait.

Çağatay *et al.* (2022) describe the very peculiar Bosphorus Strait, connecting the Mediterranean and the Black seas. The depth of the strait sill is lower than the sea-level during glacial maxima, and during lowstands the two seas, as well as the intermediate Marmara Sea, were separated. This caused strong erosion at the spillway during sea-level rise. The morphology of the strait in this tectonically active region is rather peculiar, as it is narrow (max. 3.5 km) and very long (312 km) resembling a meandering channel. In some depressions on the carved bedrock only the transgressive infilling of the last eustatic cycle is found, including fluvial, to brackish to muddy and bioclastic marine sediment, whose morphology clearly indicates an eastward-directed bottom current, driven by the water flow into the Black Sea. On the shelves facing the Bosphorus Strait, erosional valleys were carved during outflow of water when the sills were reached by water-level rise, first from the Black Sea towards the Marmara Sea and then from the Mediterranean/Marmara Sea to the Black Sea. The latter produced a spectacular channel levee system in the shelf facing the eastern entrance of the Bosphorus Strait.

Martorelli *et al.* (2022) offer a review of the Messina Strait, between the Ionian and Tyrrhenian seas in the Mediterranean. The authors present an updated morpho-sedimentary description and interpretation of the strait area, based on high resolution multibeam and reflection seismic data. They also describe and classify different types of depositional and erosional features, occurring in a variety of spatial and temporal scales. The overall picture shows a very dynamic environment from an oceanographic point of view, with semi-diurnal reversals of bottom currents, occurrence of nonlinear internal solitary waves, mass wasting phenomena, earthquakes and landslide-generated tsunamis, as well as a wide range of sedimentary features, from large drift to sand-wave fields, fan deltas, erosional scours and furrows. An interesting feature in the sill is the presence of elongate morphological features, interpreted in the past as erosional scours and here suggested to possibly represent fossil sand waves formed at low sea-level and then stabilized by encrusting biota.

Kang *et al.* (2022) and **Caterina *et al.* (2022)** present palaeoenvironmental reconstructions from the Gulf of Corinth area. **Kang *et al.* (2022)** describe the detailed sedimentology of the fine-grained silty and sandy gravity flow deposits filling the Gulf of Corinth. Using grain-size and geochemistry analyses on long well cores, centimetre- to decimetre-thick beds are interpreted to be deposited under distinct hydrodynamic conditions. The authors focus on a grain-size index to distinguish hemipelagic sediments, river-derived hyperpycnal flows, high-density plumes and 'event deposits'. The authors also infer on how deep-water sedimentation was affected by the presence or absence of a marine connection (i.e. a strait), connecting the Gulf of Corinth with global ocean circulation.

Caterina *et al.* (2022) document outstanding stratigraphic sections exposed along the man-made Corinth Canal, which connects the Aegean Sea with the Gulf of Corinth in Greece. Laterally continuous outcrops preserve the record of a Late Pleistocene tidal strait, which was closed due to regional uplift and fault activity. The authors provide field observations associated with a 3D model built using drone imaging, documenting simple and compound conglomeratic ancient dunes, also including multi-scale asymmetrical herringbone cross-stratifications.

Beelen *et al.* (2022) present a field-based description of Miocene deposits that are interpreted to be accumulated marginally to the Rifian Corridor, an ancient sea strait whose remnants crop out in northern Morocco. Vertically stacked claystones, siltstones and sandstones and a variety of sedimentary structures indicate influence of marine currents, horizontal tidal amplification and reduced wave activity in a strait-margin deltaic environment. The article also documents examples of simple and compound tidal dune architectures and critically discusses their preservation potential in the framework of the reconstruction of ancient tide-dominated environments.

Folkestad and Steel (2022) present a case study from the North Sea Early Jurassic Seaway, showing the importance that recognizing ancient straits and seaways has on feeder-system and reservoir reconstructions. They provide a new interpretation of the Lower Jurassic Cook Formation in the subsurface of the northern North Sea. This succession, which represents a well-known hydrocarbon-prolific reservoir exploited in many fields, has been thought in the past to record a westward prograding deltaic unit sourced from Norway. Based on a robust dataset of seismic and well-core data, the authors reconstruct the middle to distal reaches of a very large, north–south-oriented delta system, variably confined within the Early Jurassic Seaway running from the Norwegian Sea into the northern North Sea. This work also documents the presence of tidal sandstone ridges included in the transgressive interval of the

Cook Formation and their time-equivalence with the marginal-marine facies of the northernmost Tilje Formation in the Haltenbanken region.

Dorsey *et al.* (2022) describe the stages of flooding and re-flooding of a tectonically controlled narrow incision from the lower Colorado river valley in southwestern USA. The focus is on Miocene–Pliocene deposits of the Bouse Formation, within which facies and marine fauna descriptions indicate the flooding/transgression on top of a non-marine/fluvial system. The key point of the article is that incised valley flooding created a strait on top of a fluvial system. The stratigraphy is composed of mixed siliciclastic and carbonate sediments that record tidal facies and support a strait interpretation.

Cavazza and Longhitano (2022) show how palaeostrait sedimentary infills can be regarded as 'tectonic facies' to disentangle stages of microplate rifting in the geological record. They base their consideration on a number of palaeostraits developed during the Neogene to Quaternary in the Mediterranean, whose remnants are today preserved in outcrop successions. These examples provide snapshots of stages of microplate fragmentation and dispersal, punctuated by narrow seaways/straits where conditions of marine current amplification occurred and were recorded by characteristic large-scale, cross-stratified facies.

Puga-Bernabéu *et al.* (2022) document the influence of topography on sedimentary dynamics in the tectonically controlled tidal-dominated Zagra Strait (Betic Cordillera). The strait was governed by tidal processes responsible for the accumulation of compound-dunes with individual thicknesses in excess of 10 m. Something that seems to be a recurrent theme to the straits and seaways stratigraphy, the early Tortonian Zagra strait deposits preserved both siliciclastics and carbonate deposits. The siliciclastics and carbonate deposits of Zagra Strait have a reciprocal distribution with siliciclastics dominating the strait margins and with carbonates preserved along the strait centre.

Kalifi *et al.* (2022) illustrate the control of tectonics on the palaeogeographical evolution of the Miocene seaway along the Alpine foreland basin system in France. Detailed reconstruction of the tectonic control on the depositional environments and how these structures created constrictions at different locations through time are illustrated in a series of nine palaeogeographical maps. The reconstructions are based on previous studies, additional field data collection and laboratory results added by Kalifi and his colleagues. The >10 Ma reconstruction of the Miocene Seaway along the Alpine foreland shows the main controls were tectonics, palaeotopography (which at times segmented the seaway) and sea-level variations.

Minor *et al.* (2022) describe the upper Cretaceous shoreline and shelf sandstone deposits in the Western Interior Seaway of North America. Using previous published data and new outcrop sections, fluvial, deltaic and shelf/offshore deposits are described in multiple regressive–transgressive sequences. The sequences are reconstructed within a high resolution (a few hundred thousand years) chronostratigraphic framework based on ammonite zonations. The focus of the article is on contrasting shoreline deposits formed by mixed fluvial, wave and tidal processes with laterally equivalent tidal and basinal current-dominated shelf sandstones. The study is the first to propose the possibility that isolated sandstone bodies might be part of a double-clinoform delta geometry and also suggests the possible tectonic segmentation of the Western Interior Seaway.

The way forward

Despite a number of studies on straits and seaways, the geological understanding of these systems needs to be further investigated. As pointed out in this introduction, straits and seaways have a great influence on our modern society and ecosystems, and have been key features of past Earth's landscapes, influencing climate equilibria, warranting more studies. This volume is improving the knowledge of straits and seaways, and we hope this is just the beginning, and future studies dedicated toward the understanding of strait/seaway evolution, preserved deposits and recognition criteria will follow. We would like to emphasize the particular geological characteristics of the connections between basins, straits and seaways, because these were not always previously recognized as separate basins with their particular stratigraphy. Future research topics of interest related to straits and seaways could focus on: mechanisms of initiation and demise of straits and seaways; cyclicity (caused by sea-level changes) in their stratigraphy; tectonic styles affecting morphology and stratigraphy; processes variability during the evolution of straits and seaways and their suitability for exploitation of conventional and renewable resources. Finally, we highlight that a great step forward in the understanding of these systems would be the full integration of the knowledge and models between straits, seaways and gateways research.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

VMR: conceptualization (lead), data curation (lead), methodology (lead), writing – original draft (lead); **SGL**: conceptualization (equal), data curation (equal), methodology (equal), writing – original draft (equal); **CO**: conceptualization (equal), data curation (equal), formal analysis (equal), validation (equal), writing – original draft (equal); **FLC**: conceptualization (equal), data curation (equal), validation (equal), writing – original draft (equal).

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Data availability

All data generated or analysed during this study are included in this published article.

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