Straits and seaways: end members within the continuous spectrum of the dynamic connection between basins

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Abstract: Straits and seaways are fundamental connectors of oceans, seas and more rarely lakes. They are ubiquitous in the modern geography and should be common in ancient landscapes. We compare their characteristics to improve our understanding of these features, with the aim to define better their geological use.

We review geomorphological, oceanographic, geological and depositional characteristics based on well-documented modern and ancient examples, with a stronger focus on the rock record.

'Strait' and 'seaway' are differentiated by their spatial and temporal scale. This influences the type and persistence of oceanographic circulation and sediment distribution. Straits are individual depositional systems, with predictable bedform and facies changes along the sediment transport pathway, whereas seaways are larger and longer-lived physiographic domains, composed of numerous depositional systems. Therefore, their stratigraphic signature in the rock record should be significantly different. We conclude that straits and seaways are end members of a continuum, giving rise to the occurrence of intermediate cases with transitional characteristics. The distinctive geological usage of the terms 'strait' and 'seaway', even without sharp boundaries between end members, may be helpful for predicting their occurrence, stratigraphy, palaeogeography, biota distribution and potential distribution of reservoirs and seals for fossil resources and CO_2 storage.

Supplementary material: The data used to generate Figures 2 and 4 are available at https://doi.org/10.6084/m9.figshare.c.6299324

Straits and seaways: synonyms or antonyms?

Straits and seaways are very common features in the modern geography, and widely used terms adopted to indicate lateral marine (more rarely lacustrine) constrictions between emerged land and connecting wider basins (Fig. 1). They are key for the exchange of water, heat, nutrients and biota between different basins, as well as being highly strategic for anthropic activities (e.g. Akhmetiev and Beniamovski 2009; Flecker *et al.* 2015; Karas *et al.* 2017). Additionally, straits and seaways have been common features in the landscape throughout Earth's history, and their interpretation and reconstruction are important to accurately reconstruct the palaeogeography, palaeoecology and stratigraphy of interconnected basins (see for example Palcu and Krijgsman 2022).

Despite being often used as synonyms, strait and seaway bear rather different meanings if investigated under a geological point of view, as they show dramatic variability in spatial and temporal scales (see also Dalrymple 2022). The use of the words 'strait' and 'seaway' can overlap in publications and their geological definition is not always straightforward. Therefore, there is a need for highlighting the key differences and for identifying some general criteria that can be helpful to identify straits and seaways, which is especially needed for ancient sedimentary systems where only part of the systems might be preserved.

The geographical names (strait, pass, channel, sound, narrows, neck, isthmus, corridors, among the most used) do not follow any genetic principles, but rather refer to historical or geographical customs (Fig. 1). From the Merriam-Webster dictionary

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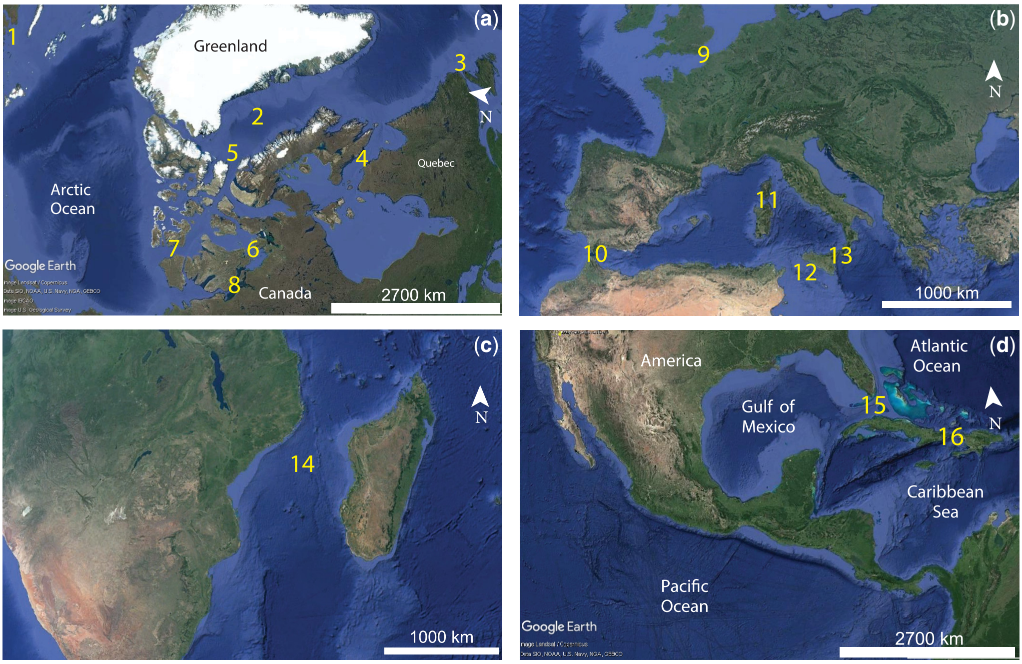

Fig. 1. Views of the Earth's surface with some examples of straits and seaways. (**a**) 1, Kara Strait; 2, Baffin Seaway; 3, Strait of Belle Isle; 4, Hudson Strait; 5, Lancaster Sound; 6, Victoria Strait; 7, McClure Strait; 8, Dease Strait. (**b**) 9, Dover Strait; 10, Gibraltar Strait; 11, Bonifacio Strait; 12, Sicily Channel; 13, Messina Strait. (**c**) 14, Mozambique Channel. (**d**) 15, Straits of Florida; 16, Windward Passage. Source: satellite images from Google Earth (Data: SIO, NOAA, US Navy, NGA, GEBCO. Image: Landsat/ Copernicus, IBCAO, US Geological Survey.)

(https://www.merriam-webster.com/dictionary/), a *strait* is 'a comparatively narrow passageway connecting two large bodies of water, often used in plural but singular in construction', while *seaway* has a rather nautical significance as 'the sea as a route for travel'. This meaning of seaway as a water passage where transfer is allowed, was maintained and even emphasized in the scientific literature, where the word acquired the meaning of a region where water masses and species may be transferred from one basin to another.

The use of the term 'strait' in geography has been applied to many passageways connecting wider bodies of water independently from their width. The Bonifacio or the Messina straits (11 and 13 in Fig. 1b) are examples just a few kilometres wide. Although Torres and Hudson (4 in Fig. 1a) are connections 100–150 km wide, they are also geographically defined as straits. This comparison shows the loose usage of the term 'strait' to define a narrowing.

Geographical and navigation maps show how the term 'seaway' has been adopted for wider sea branches, ranging in width from hundreds to thousands of kilometres. Examples are the Sierra Leone Seaway, representing the narrowest cross-section of the Atlantic Ocean, the Greenland Seaway, between NE Greenland and Svalbard Islands, or the Baffin Seaway (known also as Baffin Bay; 2 in Fig. 1a), separating western Greenland from Baffin Island.

Geologists have borrowed the loose usage of the terms 'straits' and 'seaways' in the reconstruction of marine connections of the past. However, possibly intuitively, many authors tend to differentiate passageways based on their size and time persistence when describing them in the geological record. 'Strait' has been broadly used to identify narrow and short-lived connections such as the Miocene straits forming the Betic Corridors (e.g. Martín *et al.* 2014; Puga-Bernabéu *et al.* 2022) or the Pleistocene straits that dissected the southernmost reach of the Italian peninsula (e.g. Longhitano *et al.* 2012) in the Mediterranean. Likewise, geologists use 'seaway' in the reconstruction of ancient marine wide passageways connecting large basins, such as the Cretaceous Western Interior Seaway, the Cenozoic Panama (or Central American) and Indonesian seaways, the Oligo-Miocene Tethys Seaway, the Late Quaternary trans-Antarctic Seaway, the Jurassic Laurasian Seaway, the Cretaceous–Cenozoic Baffin Seaway (2 in Fig. 1a).

Also, biological and palaeontological studies tend to differentiate straits and seaways, both modern and ancient, based on the spatio-temporal scale they represent. Straits may temporally separate biological provinces, leading to short-term differences (especially on fauna) or, on the contrary, may interconnect two adjacent, and previously isolated, marine realms with consequent fauna exchange and sharing of biodiversity. In extreme cases, the connection can lead to dramatic biota changes and invasion of alien species (e.g. Ben-Tuvia 1985; Mavruk and Avsar 2008). Seaways may represent longer-term connections between basins in different climatic zones, where persistent marine currents, capable of transporting heat, may influence the climate of entire continental-scale zones (Berggren 1982; Bjerrum *et al.* 2001; Akhmetiev and Beniamovski 2009).

Geological investigations that focus on palaeoceanograpy have also emphasized the term *gateway* to indicate long-lasting oceanic or marine connections between large ocean basins that can affect global ocean circulation and deep-water exchanges, with influence on climate (e.g. Berggren 1982; Karas *et al.* 2011, 2017; Flecker *et al.* 2015; Straume *et al.* 2020; Bahr *et al.* 2022), or in reference to the oceanographic/morphobathymetric engine that drives contouritic currents in deep-marine settings (Hollister 1993; Stow *et al.* 2009; Glazkova *et al.* 2022).

If in physical geography ‘strait’ and ‘seaway’ are thus interchangeable terms, in geology and oceanography they represent different entities based on the differences due to specific processes and distinctive spatial and temporal scales. Keeping in mind that *natura not facit saltus* (i.e. there is a continuum among natural features), one question we explore in this work is what will be the criteria according to which we start or stop calling it ‘strait’ or ‘seaway’ during the evolution of a connection between two basins, and when, for example, the seaway ends and turns into a sea/ocean with a passive continental margin.

In this article, we discuss specific aspects related to the spatial and temporal-scale characteristics of straits and seaways, their water circulation, and their facies and stratigraphic variability to extract general criteria to help define and distinguish the two end members within a continuous spectrum. The main goal of this study is to improve our understanding of these geological systems, to provide criteria, and to promote a more proper geological use of the terms ‘strait’ and ‘seaway’, based on the review of a number of documented case studies from modern and ancient examples. The focus is especially on the ancient record, where characteristics and distinctions can be more ambiguous and difficult to recognize due its fragmented nature. For example, while in modern systems it is straightforward to define the dimensions of straits or seaways (length, width, depth and cross-sectional area), this can be difficult or even impossible for ancient systems, even more so as through time the cross-sectional area(s) can change as well as the associated processes. This is why we often need to use a combination of criteria when interpreting the rock record.

Methods and datasets

This study is based on an extensive literature review of modern and ancient case studies, in order to extract information about current circulation, spatial scales, their long-term evolution and to identify typical sedimentological and stratigraphic characteristics. Additionally, an open-access bathymetry dataset has been used to further constrain spatial scale characteristics of straits and seaways. As the reader will note, we have also benefited from data and insights coming from many of the articles included in the present volume, with special emphasis on that of R.W. Dalrymple (Dalrymple 2022).

Spatial- and temporal-scale differences

The observation of the present-day geography reveals a variety of analogues for straits and seaways, offering several modern examples and case studies (Figs 1 & 2). For a comprehensive and in-depth analysis of dimensions of selected modern straits and seaways we refer to Dalrymple (2022). Bathymetric profiles across the narrowest section of 56 modern straits and seaways (Fig. 2) show the incredibly varied array of spatial scales involved, which can change over a few orders of magnitude. This figure highlights that (1) straits and seaways have an irregular profile with many of them characterized by more than one ‘deep section’, suggesting complex oceanographic circulation and sedimentary patterns; (2) some straits have an incipient ‘shelf’ with an abrupt drop at tens of metres water depth; (3) the large cross-section morphological variability likely results in variable hydrodynamic and depositional patterns, especially for examples that are around 100 m deep and are commonly exposed during low sea-level stands.

We argue that straits and seaways are the end members of a natural continuum, sharing similar geometric features (e.g. the elongation with respect to a central axis; Fig. 3), while being related to different (but partially overlapping) spatial (Fig. 2) and temporal scales. Figure 2 clearly shows that there is a continuum in dimensions of the cross-sections in modern straits and seaways but does not show clusters or trends to clearly separate the two. Figure 4 focuses mainly on ancient examples, and it highlights the continuum in space and time between straits and seaways, but it clearly identifies the two end-member groups. We have chosen to use the

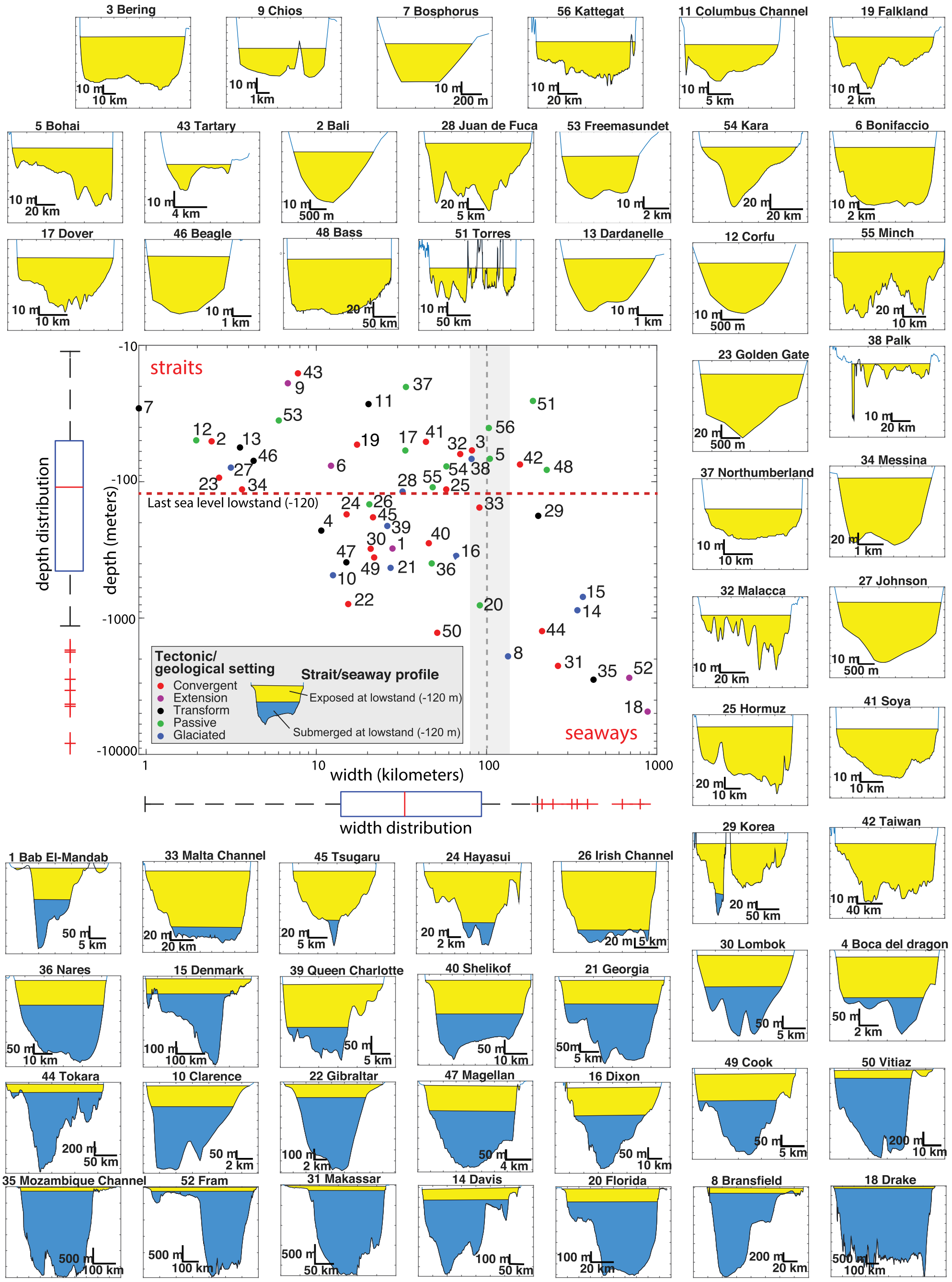

Fig. 2. Bathymetric profiles of 56 modern straits and seaways. Depth and width of the selected straits and seaways are plotted taking into account the tectonic setting. The reduction in cross-sectional area during the last glacial lowstand (−120 m) is highlighted. The location of these straits and seaways can be found in the Supplementary material.

width (as opposed to other dimensions, such as depth or the cross-sectional area), because it is the parameter that is more readily available in palaeogeographical reconstructions of ancient straits and seaways. However, depth, length and the cross-sectional area are also important parameters that can

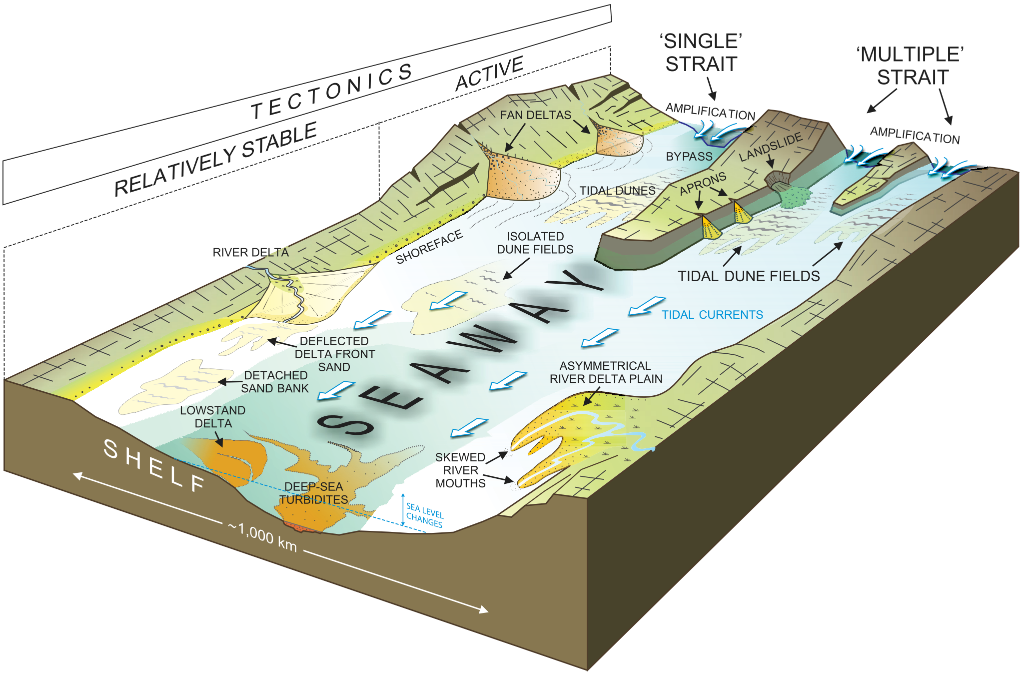

Fig. 3. Block diagram showing the major spatial difference between straits and seaways. Straits tend to be of the order of kilometres to tens of kilometres (maximum *c.* 100 km) wide passageways, representing individual depositional systems and forming single or multiple corridors. Seaways are wider features (with widths usually of the order of hundreds to thousands of kilometres), they may 'contain' straits, as well as a variety of additional depositional systems. They tend to have wide marginal shelves with prograding coastal wedge. Source: Longhitano and Steel (2016), in Longhitano and Chiarella (2020).

affect hydrodynamics and sedimentation in straits and seaways.

The end-member straits tend to be narrow corridors, a few kilometres to typically <100 km wide (Fig. 4), where marine waters are accelerated. In extremely narrow straits (kilometres to tens of kilometres wide) it is common to have bedload parting or a bypass zone, and a predictable change of bedforms along the current pathway (Longhitano 2013). In the last decade, researchers started considering straits as individual depositional systems with specific and diagnostic characteristics (e.g. Longhitano and Chiarella 2020). The end-member seaways have more complex current circulations and widths (at their maximum extent) of the order of hundreds of kilometres up to around a thousand kilometres. Consequently, seaways may 'contain' straits, as well as deltas, estuaries, contourites and subaqueous turbiditic fans (Fig. 3), capable of recording complete transgressive–regressive cycles on scales of millions of years. Based on the comparison between Figures 2 and 4, it would appear that depth is not a definitive criterion to differentiate between the end-member straits and seaways, as there is a huge overlap of depths between end-member cases and transitional ones (very deep straits can be the product of strike-slip faults, see Dalrymple (2022); very wide but relatively shallow passageways have transitional characteristics between straits and seaways, as discussed in more detail in the discussion below). It is likely that the cross-sectional area would be more important, as it has a more direct control on current movements.

From a geological perspective, the evolution of straits and seaways is recorded over different time spans in the stratigraphy (Fig. 4). As a general (but not universal) observation, the end-member straits are geologically short-term features, of the range of thousands or tens of thousands of years up to a few millions of years (Fig. 4). Their occurrence can be related to extensional tectonics, strike-slip faulting, formation of volcanic arcs, episodes of tectonic collapse of narrow portions of sedimentary basins or to sea-level rise and inundation of ancient river valleys, just to name a few possible mechanisms. Similarly, shallow straits may disappear during sea-level lowstands (e.g. Martorelli *et al.* 2022), or can be affected by significant erosion during interstadials and

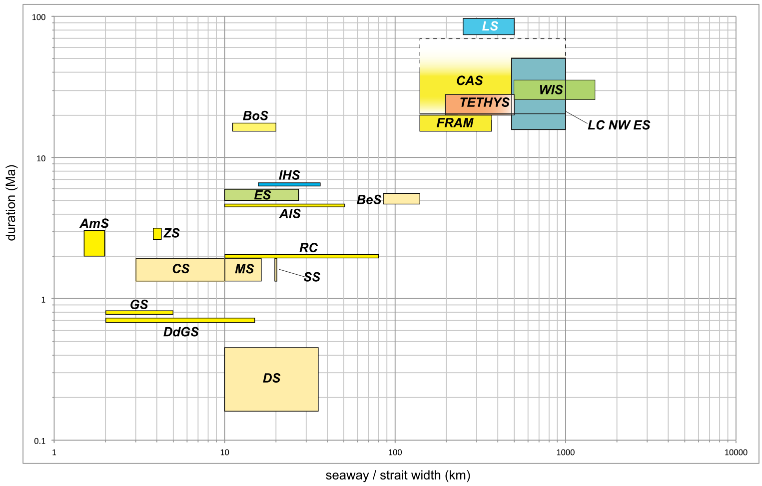

Fig. 4. Duration v. width plot of selected modern and ancient straits and seaways. The plot shows the continuum in space and time between straits and seaways, but it also highlights the two end members. Colour-coded according to the International Commission on Stratigraphy Time Scale chart. DdGS, Dehesas de Guadix Strait; GS, Guadalhorce Strait; LS, Laurasian Seaway; LC NW ES, Late Carboniferous NW Europe Seaway; ES, Elbe Strait; AmS, Amantea Strait; ZS, Zagra Strait; AlS, Alpine Seaway; CAS, Central American Seaway; WIS, Western Interior Seaway; Fram, Fram Strait; Tethys, Tethys Seaway; IHS, Inner Hebrides Strait; BeS, Bering Strait; BoS, Bonifacio Strait; RC, Rifian Corridor; CS, Catanzaro Strait; SS, Siderno Strait; MS, Messina palaeo-strait; DS, Dover Strait. References and data used to build this graph can be found in the Supplementary material.

meltwater phases (e.g. Çağatay *et al.* 2022). We also refer the readers to Dalrymple (2022) for a review of the geological origin and evolutionary model of modern straits.

There are many examples of geologically short-term opening of marine connections in the Neogene to Quaternary Mediterranean Basin (see Cavazza and Longhitano 2022, for a review). For example, the Catanzaro, Siderno, and Messina Straits formed in the Late Pliocene–Early Pleistocene as a result of regional transtensional tectonic activity that fragmented the Calabrian Arc in southern Italy into narrow basins (Longhitano *et al.* 2012, 2021*a*; Chiarella *et al.* 2016; Rossi *et al.* 2017; Longhitano 2018). Another occurrence of a relatively short-lived, fault-bounded, strait is recorded in the Cretaceous Bohemian basin-fill succession (i.e. the 10–25 km-wide Elbe Strait; Uličný 2001; Uličný *et al.* 2009). The epicontinental Bohemian Basin during the Cretaceous was micro- to mesotidal, but numerical modelling shows that tidal currents were accelerated within the narrow straits due to bathymetric constrictions (Mitchell *et al.* 2010).

The end-member seaways generally derive from longer-timescale geological processes, such as flexural subsidence, subduction and collision or to continental breakup, rifting and drifting, which can last for tens of millions of years (Fig. 4). For this reason, seaways are likely to constitute longer-lived connections between wider basins. Nevertheless, seaways can also undergo significant changes in their width at short timescales (100 kyr) due to eustatic rise and fall in sea-level (Minor *et al.* 2022).

The seaways that formed during the breakup of Pangaea (proto-Atlantic seaways; e.g. Ford and Golonka 2003; Dera *et al.* 2015; Walker *et al.* 2021), like the Laurasian Seaway (e.g. Ziegler 1988; Doré 1991; Bjerrum *et al.* 2001) or the Hispanic Corridor (e.g. Porter *et al.* 2013), best exemplify the formation of large seaways due to rift-to-drift evolution, from shallow and narrow seaways developed on rifted continental crust to fully oceanic seaways (Porter *et al.* 2013). During the initial phases of rifting and marine flooding, detailed palaeogeographical reconstructions are essential in order to distinguish the presence of multiple straits connecting smaller basins and graben, which eventually coalesce forming a larger seaway.

The Laurasian Seaway (LS in Fig. 4) connected the Tethys to the Boreal Sea (Fig. 5). From the Mid-Permian, extensional faulting allowed marine transgressions into the proto-North Atlantic rift, even though, throughout the Triassic, no continuous connection existed and continental deposition dominated (Fig. 5; Ziegler 1988; Doré 1991). As the Atlantic rift continued, marine transgressions gradually established an open seaway during the Jurassic (Fig. 5), even though palaeo-highs were at times present within the rift domain and uplift events intermittently restricted the marine

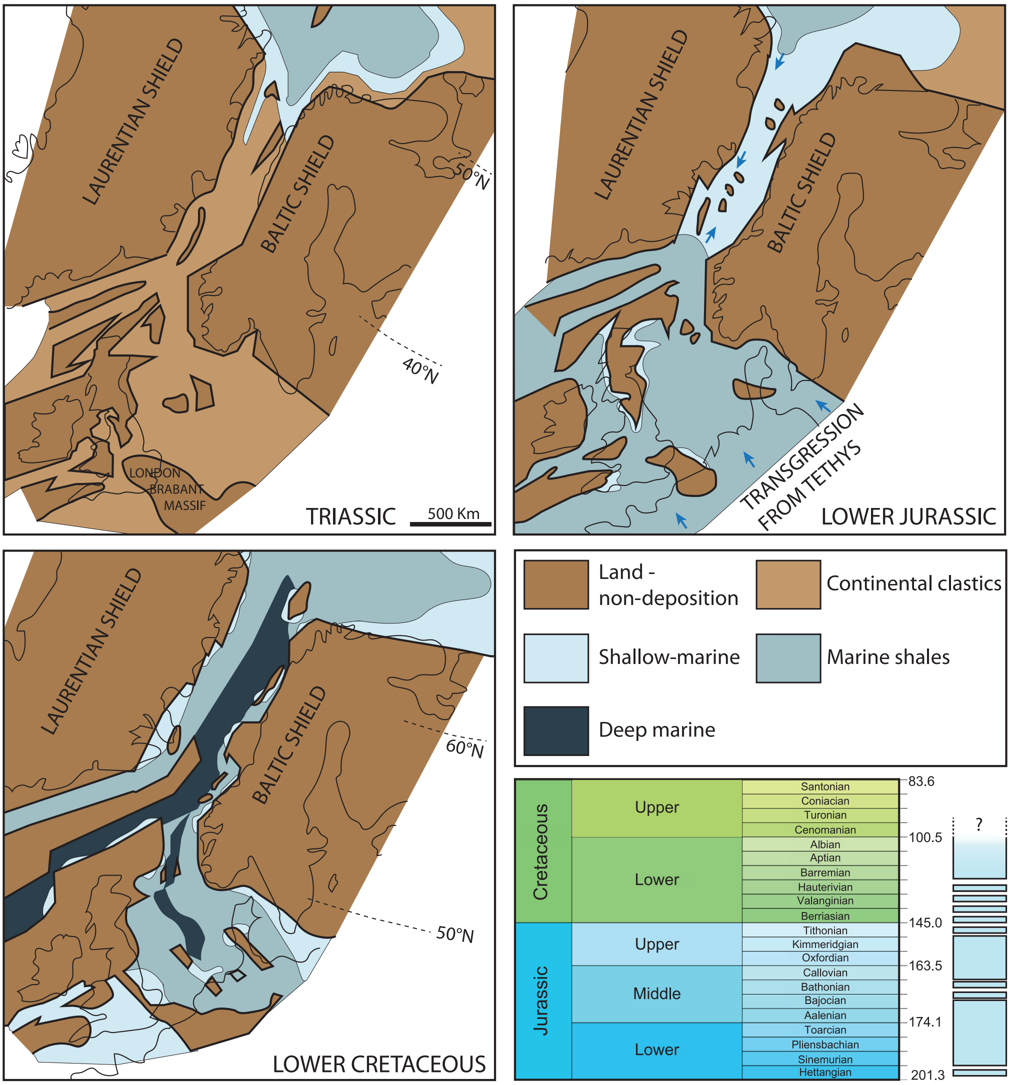

Fig. 5. Evolution of the Laurasian Seaway from the Triassic to the Lower Cretaceous (palaeolatitudes are indicated). Source: redrawn from Doré (1991).

connection (Doré 1991). The seaway was permanently open starting from the Aptian–Albian due to transgressions and oceanic basins formation (Doré 1991). During the seaway evolution, intra-rift uplift may have caused the occurrence of islands and smaller straits within it, and the formation of land barriers that controlled faunal provinciality and reduced the warm–cold water exchange (Doré 1991; Bjerrum *et al.* 2001; Korte *et al.* 2015; Brikiatis 2016).

When do we consider the seaway to end? We can expect the end of the seaway to be likely gradual, marked by the development of oceanic floor spreading and oceanic crust, until the seaway exceeds the cross-sectional area (width and depth) at which it can accelerate currents at shelfal depths. We do acknowledge that deep bottom currents, such as contour currents, can remain active and locally accelerate where they interact with bathymetry, even when a seaway has fully evolved into an ocean basin, as they are influenced by regional or global oceanic circulation and local physiographic constraints of the basins (e.g. Hernández-Molina *et al.* 2008; Rebesco *et al.* 2014).

The Cretaceous Western Interior Seaway (WIS in Fig. 4) represents an example of a large epicontinental seaway (at times with a width of up to 1500 km) that formed in a retro-arc foreland basin. The basin developed due to a combination of flexural subsidence from the loading of the Sevier Orogen and dynamic subsidence caused by the corner flow in the mantle due to the subduction of the Farallon and Kula plates (DeCelles 2004; Liu and Nummedal 2004; Liu *et al.* 2014). From the Early Cretaceous, the Boreal Sea began its southward transgression (e.g. Peng *et al.* 2022), eventually flooding the entire basin and creating a connection from the Arctic to the Gulf of Mexico (Fig. 6).

How did the WIS ended? At the end of the Cretaceous, a change in the angle of the subducted plate caused a reorganization in the stress field in the overriding plate, modifying the subsidence patterns of the basin, creating Laramide-style uplifts as early as the Campanian and a shallowing of the basin (Cross 1986; DeCelles 2004; Leva López and Steel 2015). This caused the seaway to end, initially through a closure of the connection to the Boreal Sea (Minor 2022), and later as the connection to the Gulf of Mexico closed, even though the basin persisted as a narrowing epicontinental sea until the end of the Maastrichtian and tenuous connections to both the Gulf of Mexico and the Boreal Sea intermittently occurred through Paleocene time (Minor *et al.* 2022).

The Tethys Seaway (Fig. 7) is another good example of a long-lasting opening/closure of connection between adjacent oceanographic domains. It linked the eastern proto-Mediterranean Sea with the Indo-Pacific Ocean mainly during the Eocene (Figs 4 & 7a; Straume *et al.* 2020). As a consequence of oceanic crust subduction and collision between Arabia and Eurasia (Allen and Armstrong 2008; Okay *et al.* 2010), the Tethys Seaway gradually began to close. During the Oligocene, the seaway was shallow (Allen and Armstrong 2008; Straume *et al.* 2020), possibly intermittently opened, with a configuration that can possibly be compared to the modern Indonesian Seaway (see also Bahr *et al.* 2022). The final closure of the Tethys Seaway (Fig. 7d) around *c.* 20 Ma (Okay *et al.* 2010; Straume *et al.* 2020) coincides with the first land animal migration at *c.* 19 Ma (Harzhauser *et al.* 2007), and shows how the closure of a seaway can become an important biological connector for life species living in subaerial realms (another example being the closure of the Central American Seaway in the Pliocene; Straume *et al.* 2020).

Oceanographic circulation in straits and seaways

An important difference between the end-member straits and seaways is related to their oceanographic circulation. In general terms, owing to their spatial and temporal scale differences, the volume of water masses involved in these two systems is dramatically different, as well as the way in which water masses interact within lateral constrictions. The focus is on the dominant circulation and transport modes for the end-member straits and seaways. For an in-depth review of the different types of currents occurring in straits and seaways, we refer readers to Dalrymple (2022).

Hydrodynamics of straits

Processes in straits are essentially related to convergence and acceleration of masses of water, transiting mostly sub-horizontally and passing through a main constriction of the cross-sectional area. This apparently simple setting is the main ingredient for the amplification of marine currents, which can be

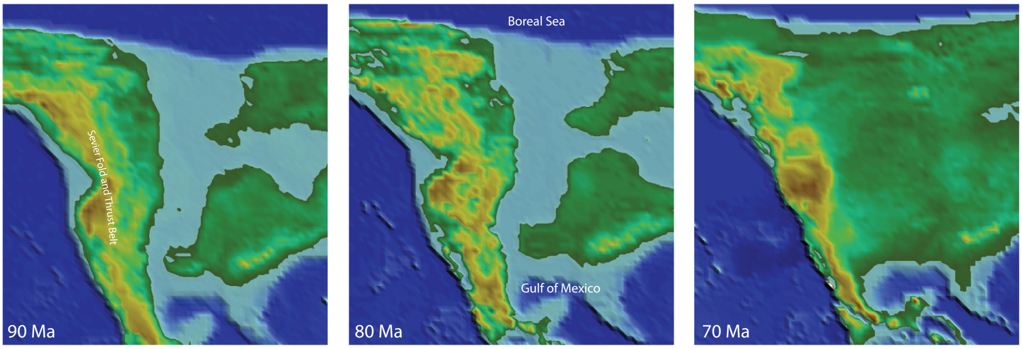

Fig. 6. Late Cretaceous evolution of the Western Interior Seaway, from the Turonian (Cretaceous global highstand) to its closure in the Maastrichtian. Source: grids from Scotese and Wright (2018), PALEOMAP Paleodigital Elevation Models (PaleoDEMS) for the Phanerozoic.

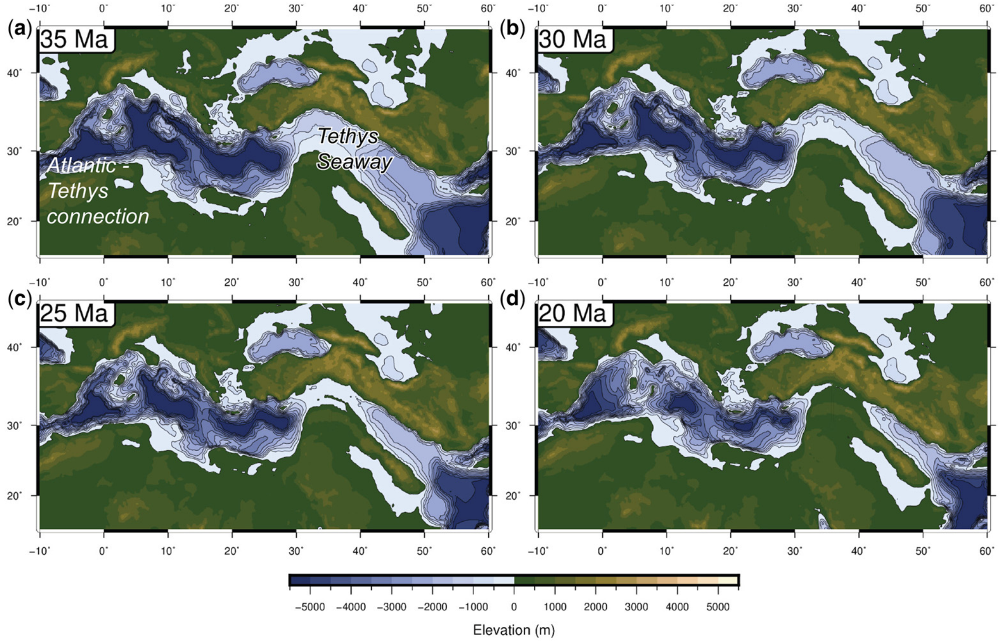

Fig. 7. (**a–d**) Long-lasting development of the Tethys Seaway, between the proto-Mediterranean and the Indo-Pacific Ocean, from the Late Eocene (a) to its definitive closure around 20 Ma (d). Source: after Straume *et al.* (2020).

generated by rise of water masses above their natural depth, generation of internal waves and tidal inversions, as well as density differences between the interconnected basins (for a thorough discussion on the processes see Dalrymple 2022).

In straits (and seaways) water exchange between the basins can have different origins and complex temporal and spatial circulation patterns controlled by connection morphology, sectional area, length and water properties (density, temperature). However, tidal-generated currents have historically been studied more than other processes in straits and seaways, and as a consequence they are more represented in this section. A key insight for the understanding of strait dynamics was the role of horizontal tidal amplification. Colella (1996) argued that no large vertical tides are required to produce tidal influence where a reduction of the cross-sectional area enhances the effect of horizontal tides. Indeed, even in modern microtidal marine settings, tides may be locally reinforced when their diurnal or semi-diurnal vertical movements change into horizontal transfer of water masses that are compressed through a reduced hydraulic cross-section, generating tidal amplification (e.g. Longhitano 2011). The process of horizontal current amplification, which applies also to meteorological, oceanic and density-driven currents, may be replicated at every further restriction

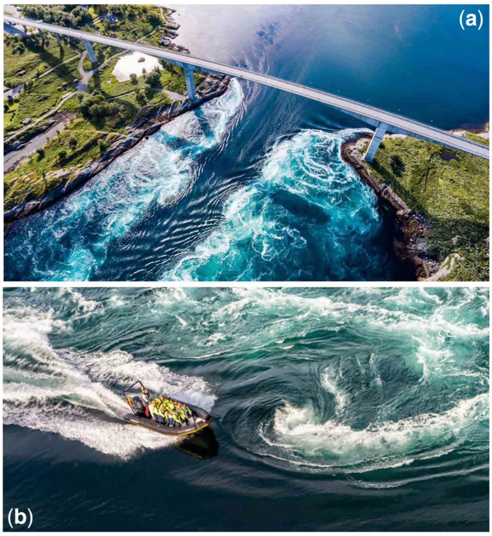

Fig. 8. (**a**) The Saltstraumen Strait in Norway that holds the record for the fastest current in the world (up to 37 km h^{-1}). The strait separates the Saltfjorden Fjord from Skjerstad Fjord between the islands of Straumøya and Knaplundsøya and is crossed by the Saltstraumen Bridge (768 m long). (**b**) Detail of one of the vortexes formed during the transit of a fast current. Boat for scale is *c.* 8 m long. Source: photo by M. Zylmann.

occurring along complex, multi-throat straits, creating catenary phenomena of flow acceleration. The same current then decelerates, as the lateral/vertical constrictions of the strait enlarge. Importantly, straits are commonly, but not exclusively, *loci* of intense turbulent flows (Fig. 8). Water perturbations may occur as vortices and eddies, related to sudden acceleration of horizontally moving currents, as portrayed in ancient mythology (e.g. the myth of Scylla and Charybdis in the Messina Strait). For example, at the Saltstraumen of Norway (Fig. 8a) *c.* 400 × 10^6 m^3 of seawater transit across the strait with speeds of up to 37 km h^{-1} (Eliassen *et al.* 2001) producing vortices up to 10 m in diameter (Fig. 8b) and 5 m in depth. However, even in highly energetic straits, there might be areas within the strait that have tranquil flows and are not affected by turbulent flows (e.g. Strait of Magellan, see Dalrymple 2022).

Straits can be affected by reversing currents, reflecting the opposing phases having roughly the same velocity (e.g. the Cook Strait between the two main islands of New Zealand). In other instances, straits may be characterized by one ‘dominant’ tidal phase, or meteorological current, reinforced because of topographic–bathymetric influences or due to phenomena of density differences between the two reversal flows (e.g. the Gibraltar Strait; Menai Strait; Kattegat; see Dalrymple 2022 and references therein).

In general terms, a major difference between straits (especially shallow and relatively short and narrow straits) and other ‘conventional’ shallow marine, coastal and paralic systems (e.g. estuaries, deltas and flats), is the direction of the flow. If currents in tide-dominated/influenced and other classical coastal systems generally approach the coastline at a high angle, in straits the main core of flows moves parallel to it (Fig. 9). This main difference in the current directions is reflected on the sediment distribution patterns and the resulting elongation trend of sand bodies along the main sediment transport routes (Belderson and Stride 1966; Belderson *et al.* 1982; Harris *et al.* 1995; Stow *et al.* 2009; Longhitano and Steel 2016; Longhitano and Chiarella 2020). The concept of ‘flood’ and ‘ebb’ used for inshore settings, referring to the landward and seaward movements of tidal currents, cannot be directly applied to straits (see for example the case of Menai Strait, as reported in Dalrymple 2022 and references therein). The identification of ‘flood’ and ‘ebb’ phases in descriptions of ancient deposits is even more difficult, as none of these flows move towards (flood), or away from (ebb) the coastline, such as in coastal tidal systems (Fig. 9a). Nevertheless, the flood current in a strait could be defined as the tidal phase directed towards the smaller or more oceanographically enclosed basin, which is internal with respect to the open ocean (Defant 1958). The reversal flow originated after every half-tidal cycle and thus represents the ebb tidal phase. When flood and ebb tidal currents transit through the narrowest strait-centre zone they follow collinear and adjacent pathways roughly parallel to the strait margins because of the constriction, whereas they

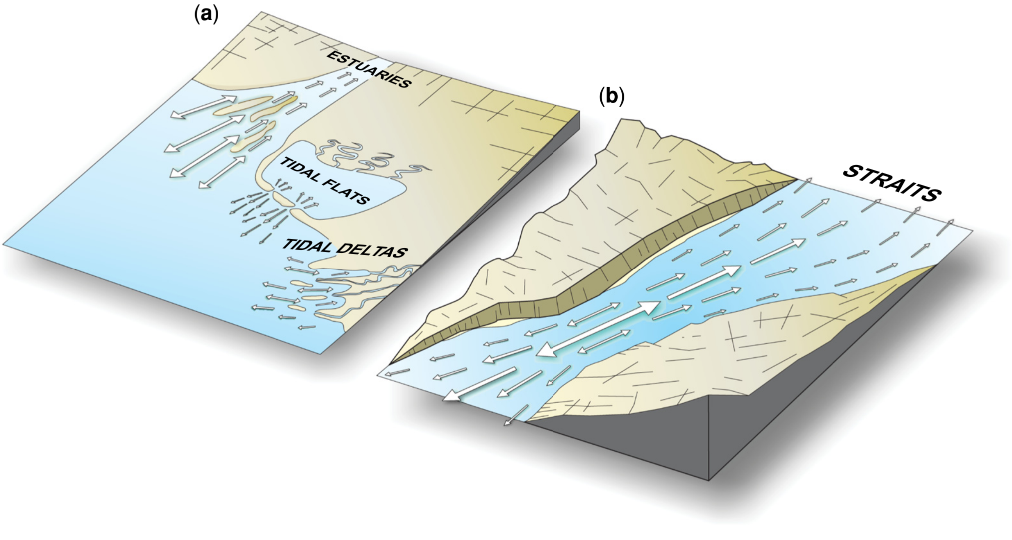

Fig. 9. Comparison between conceptual models of (**a**) a conventional tide-dominated coastal system (with estuaries, tidal flats and deltas) and (**b**) a tidal strait depositional system. The length of the arrows indicates the relative strength of the currents. Source: after Longhitano and Chiarella (2020).

expand in divergent ways or form eddies when the strait enlarges distally (Pugh 1987).

It is important to keep in mind that strait oceanographic processes can be deeply modified by eustatic changes (Fig. 2), especially those of high amplitude (as during the Late Carboniferous, Early Permian, Late Miocene, Pliocene and Pleistocene glaciations). For example, in the Quaternary, if the sill is within 100–120 m of water depth (i.e. in Sunda, Malacca, Messina, Bonifacio, Jeju, Tatar and Cook straits; see also Fig. 2 and Rossi *et al.* 2022) the water circulation can be hindered, land bridges may form and straits become subaerially exposed during sea-level lowstands (e.g. Bird *et al.* 2005; Antonioli *et al.* 2014; Lee *et al.* 2022). During the Last Glacial Maximum, this had enormous implications for the migration of land animals and early human populations (e.g. Dobson *et al.* 2020). Even in cases where the sill is deeper (e.g. Gibraltar, Bab el-Mandeb, Tsugaru straits) the circulation of water masses varies significantly between glacial and interglacial periods (e.g. Rohling and Zachariasse 1996), because the oceanographic processes are affected by the dramatic change in morphology (e.g. Kuroshio Current; Kao *et al.* 2006) (see also the model presented in Dalrymple 2022).

Hydrodynamics of seaways

From an oceanographic point of view, seaways are a key component of the global ocean circulation, as they can influence oceanic heat transport (e.g. Berggren 1982; Zachos *et al.* 2001). In seaways, marine currents are induced to flow axially due to the geographical narrowing and elongation but, commonly, with no substantial processes of water turbulence and whirlpools. However, there are also exceptions in large straits which have tranquil flows in parts of their section (e.g. Magellan Strait, Dalrymple 2022). Wind and storm waves may play a more important role if compared with straits, because of the larger internal fetch (see also Dalrymple 2022). Additionally, water motion in seaways may be more easily affected by the Coriolis effect (especially at high latitudes), which is capable of modifying the expected alongshore pattern of marine currents by imparting rotatory circulations, which move in a clockwise direction in the Northern Hemisphere and in a counter-clockwise direction in the Southern Hemisphere, due to the Earth's rotation. The presence of landmasses and bathymetric constraints are important and can modify the flow pattern, by forcing water masses against the coast and inducing a counter-clockwise circulation in Northern Hemisphere basins (e.g. Millot and Taupier-Letage 2005). Since the Coriolis Effect is usually better expressed in seaways, circulation in seaways tends to be more complex than in narrower straits, which, coupled with their overall larger dimensions (e.g. length) produces more process variability (see Dalrymple 2022). Seaways can be very important elements of the regional or global oceanic circulation, allowing the passage of surface or intermediate water masses, or allowing the exchange of deep-water masses if they become deep enough. On the contrary, they can restrict deep-water circulation between larger seas or oceans if they become too shallow (e.g. Hernández-Molina *et al.* 2008; Straume *et al.* 2020).

Currents in seaways can have a flow pattern that shares similarities with both straits and 'classical' clastic coastal depositional systems with shore-normal tidal currents. Currents can flow parallel to the seaway axis (e.g. Bjerrum *et al.* 2001; Roberts and Sydow 2003; Storms *et al.* 2005; Preu *et al.* 2011; Minor *et al.* 2022), especially at times when the seaway width is reduced (for example during lowstand phases; e.g. Dalrymple 2010; Steel *et al.* 2012). Thanks to the wider and longer dimensions of seaways, it is easier for marine currents to develop a shore-normal trend, flowing perpendicularly to the coast, at multiple coastal invaginations, in and out of the distributary channels and possibly up the trunk river channel (see for example the lower Sego Sandstone in the Cretaceous Western Interior Seaway, or the Mahakam Delta along the Makassar Strait (here considered to be a seaway, despite its name); Roberts and Sydow 2003; Storms *et al.* 2005; van Cappelle *et al.* 2016). Of course, local irregularities in the coastline or the presence of tributary rivers could allow also the development of margin-normal flows in straits, but in seaways this behaviour is much more common and regionally widespread.

The giants: trans-continental seaways of the past

Through geological time, large seaways have been able to connect oceans and basins in the tropics with high-latitude oceans and basins, linking different climatic zones (Bjerrum *et al.* 2001). As a result, their current circulation was mainly governed by hydrostatic sea-level differences, density differences and thermohaline circulation ('thermohaline' defines a system driven by movements compensating density difference, the latter due to both temperature and salinity; Bjerrum *et al.* 2001). Additionally, if seaways are deep and long enough, formation of deep-water convection and warm water advection are known to release heat and moisture to the atmosphere, thus controlling local or regional climate and continental weathering (e.g. Lear *et al.* 2003; Dera *et al.* 2015; Bahr *et al.* 2022).

Examples include the Cretaceous Western Interior Seaway, which connected the Boreal Sea with the Gulf of Mexico, and the Laurasian Seaway, that connected the Tethys Ocean with the Boreal Sea. As previously discussed, the Laurasian Seaway, by Early Cretaceous times, was strongly affected by the development of the Atlantic Rift and subsequent major transgressions, such that it effectively allowed fauna migration between Spitsbergen and the Mediterranean areas (Doré 1991). Even during the Jurassic, it was a major migration route for Arctic species towards lower latitudes (or vice versa) (e.g. van de Schootbrugge *et al.* 2020; Walker *et al.* 2021). Additionally, the increase or reduction of warm- and cold-water masses exchanges within the Laurasian Seaway has been linked to climate changes (Korte *et al.* 2015). The Northern–Central Eurasian Seaway (see also Palcu and Krijgsman 2022) was another example of a large epicontinental seaway, composed of multiple basins and straits that connected warm waters of the Paratethys to cold palaeo-arctic waters (Akhmetiev and Beniamovski 2009). It was active during the Paleogene (Paleocene to early–mid Eocene), and its closure had dramatic consequences on climate and biota (Akhmetiev and Beniamovski 2009). Even though some parts of the seaway remained active through the Eocene (e.g. the Turgai Strait; Akhmetiev and Beniamovski 2009; Palcu and Krijgsman 2022), the connection between warm low-latitude and cold Arctic waters was lost due to increased relief caused by tectonic activity.

Similarly, large east–west-oriented seaways can provide a circum-global connection between different oceans, as was the case during the early Cenozoic when the Tethys Seaway, the Central American Seaway and the Indonesian Seaway were open (e.g. Berggren and Hollister 1977; Straume *et al.* 2020) (Fig. 10a). The opening of the Drake and Tasmanian passages has allowed the development of the Antarctic Circumpolar Current which flows undisturbed by any physical barrier, isolating the coast of Antarctica from the global circulation, thus favouring the formation of dense water to feed deep-ocean circulation (see also Bahr *et al.* 2022). In the Early Cenozoic, the Tethys Seaway connected the world major oceans at a low latitude (Fig. 7; Straume *et al.* 2020). Its shallowing could have enhanced deep-water formation in the North Atlantic, and therefore this seaway

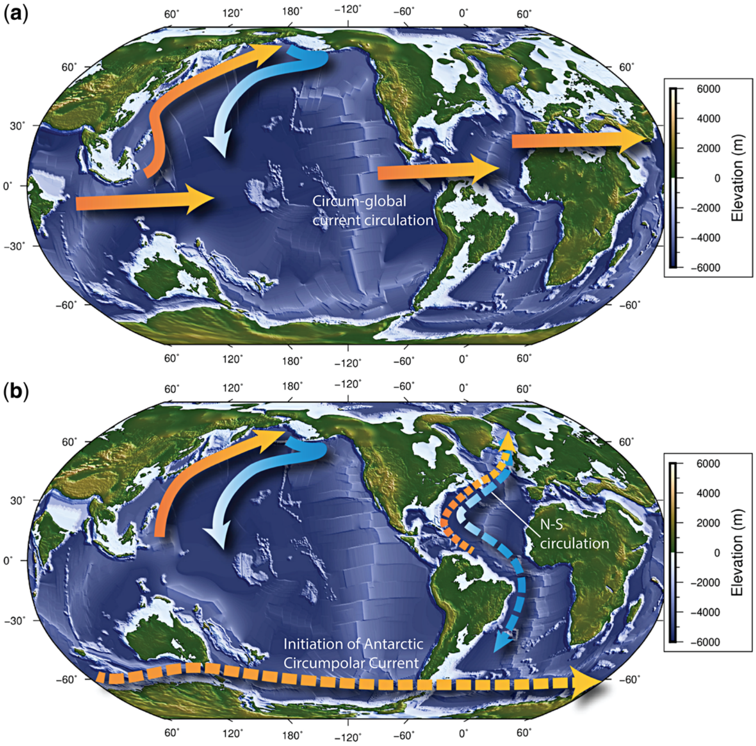

Fig. 10. Global palaeobathymetry and palaeotopography during (**a**) the Early Eocene and (**b**) at the Eocene–Oligocene transition. Arrows indicate ocean circulation patterns (orange, surface currents; blue, deep water). In (a) ocean circulation is enhanced through the east–west-oriented major seaways active at that time, while in (b) the closure of these seaways established a global oceanographic circulation with preferential north-to-south routes similar to the present-day setting. Source: Straume *et al.* (2020).

became a key climate modulator during the Late Eocene/Oligocene (Straume *et al.* 2020 and references therein). In the Mesozoic, starting from the Early Jurassic, the Hispanic Corridor opened along the Central Atlantic rift zone, connecting the western Tethys and Panthalassa (Eastern Pacific), and impacting ocean circulation and faunal connections (Porter *et al.* 2013).

Because of the Earth's rotation, the eastward-flowing currents in these equator-parallel seaways would have presumably been strengthened while transiting through them (Fig. 10). The stronger eastward currents enhanced the heat diffusion at these latitudes and promoted important flora and fauna biodiversity (e.g. Tethys Seaway, Central American Seaway, Indonesian Seaway; Fig. 10). When these seaways closed or significantly shallowed, currents and heat-flow transport changed to a dominantly north–south pathway (see Straume *et al.* 2020; Fig. 10).

Facies and stratigraphic variability

Straits

One of the most outstanding and diagnostic sedimentary signatures of straits is the occurrence of vertically stacked, large-scale cross beds (Fig. 11), occurring in either siliciclastic or carbonate sediments, and thicker than typical upper-shoreface intervals. This type of

Fig. 11. Examples of large-scale cross bedding in sandstone deposits, interpreted as the record of vigorous currents in ancient straits. (**a**) The mid Jurassic Bearreraig Sandstone in Scotland. (**b**) The upper Miocene Bonifacio Formation, southern Corsica. (**c**) Cross bedding in the lower Pleistocene Messina Strait. (**d**) Bi-directional foresets attributed to tidal reversal currents propagating through the north Betic Strait in the Tortonian of southern Spain. Arrows indicate the direction of foreset accretion. Source: (a) Archer *et al.* (2019), (b) Reynaud *et al.* (2013) ; (c) Longhitano (2018); (d) modified after Martín *et al.* (2014).

recurrent lithofacies is formed by the superposition of trains of bedforms, as the persistent acceleration of currents due to the constriction enhances bed-shear stress (e.g. Allen 1980). One recurrent characteristic of strait axial sedimentary infill is the general lack of mud and the presence of localized erosion, due to current acceleration that prevents silt- and clay-sized particles from settling, and possible erosion and scouring in the sill area (Longhitano 2012, 2013; Longhitano and Chiarella 2020; Dalrymple 2022). It is worth noting that strait deposits might not be prone to a high preservation potential, due to the very nature of strait formation, often linked to active tectonics, as previously discussed.

Sediment transport occurs as bedload and as suspended load, depending on the current energy and sediment-grain size. Where currents are accelerated, scouring, erosion and sediment bypass can occur. Accumulation may occur preferentially in those zones of a strait where currents decelerate, due to the overall enlargement of the cross-sectional area or to the morpho-bathymetric irregularities that may create conditions of local depletion of the main energetic flow. These erosional/depositional features are common to many modern straits and are the foundation of the four-folded depositional model provided by Longhitano (2013), which was developed with particular reference to tectonically confined tidal straits (Fig. 12a). This model, also applicable to meteorologically- or other current-dominated straits (see Andreucci *et al.* 2022; Dalrymple 2022), suggests some diagnostic stratigraphic sequences and facies features (Fig. 12b) that can be used to describe and recognize modern and ancient current-dominated strait-fill successions (see Longhitano and Chiarella 2020; Andreucci *et al.* 2022; Dalrymple 2022). In clastic-dominated straits, sedimentation can be expected to occur in four adjacent depositional zones (A–D in Fig. 12a), which undergo different current regimes and bed-shear stress. A by-pass zone corresponds with the area where currents exert erosion rather than deposition (Zone A in Fig. 12a). Here, sediments may form gravel furrows or discontinuous patches evolving into ribbons down current. This zone merges into a major depositional zone, the *constriction-related* delta, suggested by Dalrymple (2022), where a variety of bedforms develop (Zone B in Fig. 12a).

Since currents in straits flow in a prevalent alongshore, axis-parallel direction, sediment distribution is expected to reflect a predictable pattern of bedform *continuum* (Fig. 12a). The variety of bedforms along

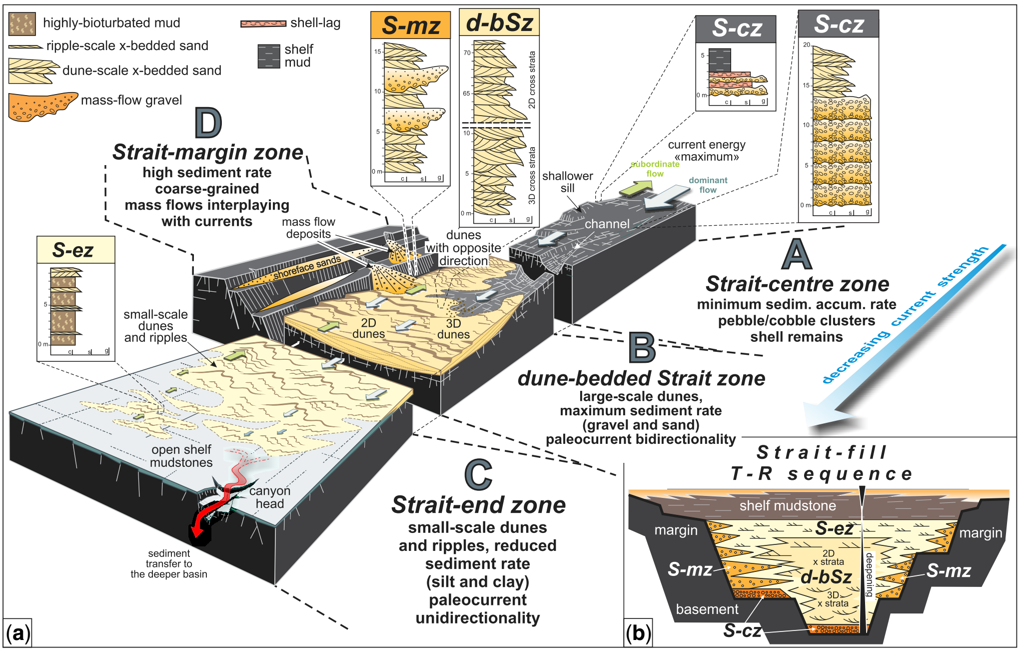

Fig. 12. (**a**) Conceptual depositional block diagram based on Longhitano's (2013) model, indicating the four major depositional zones (A–D) applicable to modern and ancient current-dominated straits. In the block diagram, the main sedimentary processes correspond with key stacking of facies that can be used as proxies for similar successions preserved in the rock record. (**b**) Cross-sectional scheme of a transgressive-to-regressive (T–R) strait-fill sequence. *S-cz*, strait-centre zone; *d-bSz*, dune-bedded Strait zone; *S-mz*, Strait-margin zone; *S-ez*, Strait-end zone.

a strait axis may originate with size scaling with the strength of the dominating current, although they may also reflect changes in water depth and sediment availability with strong similarities with what occurs in modern shelves (Belderson *et al.* 1982) and estuaries (Dalrymple and Rhodes 1995). In high-energy straits sediment transport pathways can diverge from bedload parting zones (Harris *et al.* 1995), away from which sediments accumulate, or can be unidirectional or asymmetric. The likely consequence is that the grain-size trend overall shows an increase from the strait margin towards the strait centre depositional zone, or in the presence of sandy strait-margin paralic systems, it may show first a decrease and then an increase towards the high-energy axial zone. At the same time, the grain sizes decrease along the axial sediment transport pathway, from the erosional or bypass zone towards the wider or deeper distal depositional areas.

Barchanoid to sinusoidal dunes may be observed, whose crests are elongated approximately perpendicularly with respect to the direction of the dominant current (Fig. 12a). Three-dimensional dunes transit into two-dimensional, straight-crested dunes which, in turn, evolve further down-current into linguoid to undulatory ripples and smaller sedimentary structures (Fig. 13). This bedform transition may frequently be observed in the main depositional area of a strait (Zone B in Fig. 12a), and it is associated with a decreasing grain-size trend, so that the zones located more distally with respect to the area of current velocity maxima are subject to low(er) energy and can accumulate finer-grained deposits (Zone C in Fig. 12a; see also Dalrymple 2022). In many straits, this bedform distribution can be common to both depositional sides (e.g. the Golden Gate (Fig. 13a), Cook and Messina (Fig. 13b) straits, among others), but characterized by opposite direction of bedload transport and often by different dimensions. The margins of a strait can be highly depositional zones, where paralic systems, such as river deltas, shoreface beach-barriers and lagoons may develop (Zone D in Figs 12a & 13; e.g. Longhitano *et al.* 2017; Rossi *et al.* 2017; Telesca *et al.* 2020), but these systems do not produce the dominant stratigraphic signature of strait deposits. These strait-marginal systems may receive a variable influence from the axially-flowing current pattern, changing their sedimentary features accordingly, i.e. with a deflection in the direction of the dominant flow (Longhitano and Steel 2016; Rossi *et al.* 2017; Longhitano *et al.* 2021*b*) or by amplifying the local effect of tides.

Sand ridges have been documented in current-dominated modern and ancient straits (e.g. Dyer and Huntley 1999; Messina *et al.* 2014; Longhitano *et al.* 2021*a*; Dalrymple 2022). Examples of such elongated large bedforms can be observed in the Palk Strait between the southern Indian Peninsula and Sri Lanka, the Torres Strait separating northern Australia from southern Papua New Guinea, and the Strait of Dover between France and the UK. Ridges derive from major net-sediment transport pathways, the interplay among tidal currents and oceanic currents, storms and waves, and the direction of migration of the superimposed bedforms (Huthnance 1982*a*, *b*; Belderson 1986; Dyer and Huntley 1999; Reynaud and Dalrymple 2012). However, ridges should be more common in seaways (e.g. Leva López *et al.* 2016; Minor *et al.* 2022), where oceanographic currents may persist long enough to ensure the building and the evolution/accretion of such large-scale, long-lasting bottom features.

In some rare instances, straits may resemble the morphology of channels (straight or sinuous) which were active during the sea-level lowstands, in particular structural settings when the seal is shallow, the difference in water level between two connected basins is exceptionally large and the strait's flows have strong density differences. In these particular cases, the sedimentary features and hydrodynamics may form at the lowstand and then continue to resemble those of fluvial channels. Present-day examples are the Bosporus and Dardanelles straits (Çağatay *et al.* 2022) that connect the Mediterranean to the Black Sea, whilst during lowstands a similar feature characterized the English Channel, connecting the Atlantic Ocean to a proto North-Sea glacial lake (Gupta *et al.* 2007). In general, this type of strait can be considered anomalous, short-lived and tied to active tectonics (e.g. Bosporus and Dardanelles) or mega-flood events (e.g. Ryan *et al.* 2003). Megafloods due to breaching of an ice dam may potentially create or re-shape river valleys, which can then become preferential paths for exchanging water masses between different basins (e.g. the Strait of Dover).

Seaways

Due to their wider dimensions, seaways resemble conditions most common to shelves or open-marine settings (e.g. Suter 2006). Sedimentation is likely to occur in a variety of depths yet significantly different from straits, under the influence of alongshore current circulation and resulting axis-parallel net sediment dispersal patterns, which can vary with the sea-level, such as was shown in the Western Interior Seaway (Steel *et al.* 2012; Minor *et al.* 2022). In seaways, river deltas may prograde for several tens of kilometres perpendicularly with respect to the basin axis, for example during periods of long-lasting sea-level falls (e.g. Steel *et al.* 2012). However, as progradation continues, they are likely to become influenced by alongshore currents in their delta front and

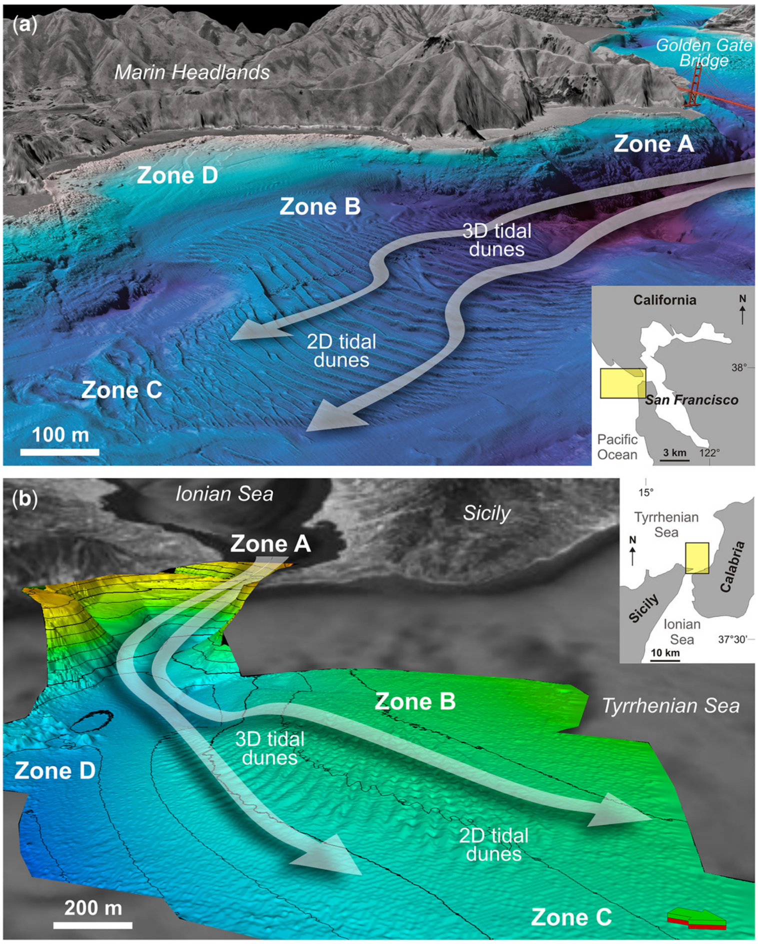

Fig. 13. Multi-beam-based bottom reliefs representing examples of strait depositional zones detectable at the exit of two modern tide-dominated systems. (**a**) The San Francisco (or ‘Golden Gate’) Strait exhibits a strait-centre zone deeper (–85 m) than its depositional areas (*c.* −30 m). Tidal flows (arrows) scour this narrowest zone and accumulate sand-size deposits in the Zone B, shaping 3D-to-2D tidal dunes that transit in the western distal portion of the strait in the Atlantic Ocean into smaller bedforms. The average sand-dune height is *c.* 6 m, their wavelength >200 m. (**b**) An analogous zone partition can be seen in the northern exit of the Messina Strait. Source: (a) modified after Dartnell *et al.* (2006).

prodelta region, causing their prodelta fine-grained sediments to change orientation (Roberts and Sydow 2003; Longhitano and Steel 2016; Dalrymple 2022). The Klang River Delta in the Malacca Strait, separating Sumatra from the Malay Peninsula, is a good example of this type of setting. The Cretaceous Western Interior Seaway provides an outstanding case study that includes several river deltas prograding into the seaway from the western margin and becoming more tidally influenced during their regressive pathway towards the seaway centre (Steel *et al.* 2012). In general terms, in seaways the grain-size trend is overall fining towards the basin axis (see Archer *et al.* 2019), transversely from the margins, in contrast with the grain size trend typical of narrow straits, where the strait axis is usually dominated by high-energy and coarse-grained facies (Rossi *et al.* 2017; Archer *et al.* 2019). This trend is dependent on the sea-level and the strait/seaway cross-sectional area. However, it is especially true at times of high sea-level, whereas during lowstands the axial transport can potentially become more prominent, even in large seaways such as the Western Interior Seaway.

Another key characteristic of seaways is their overall stratigraphic architecture, which reflects the

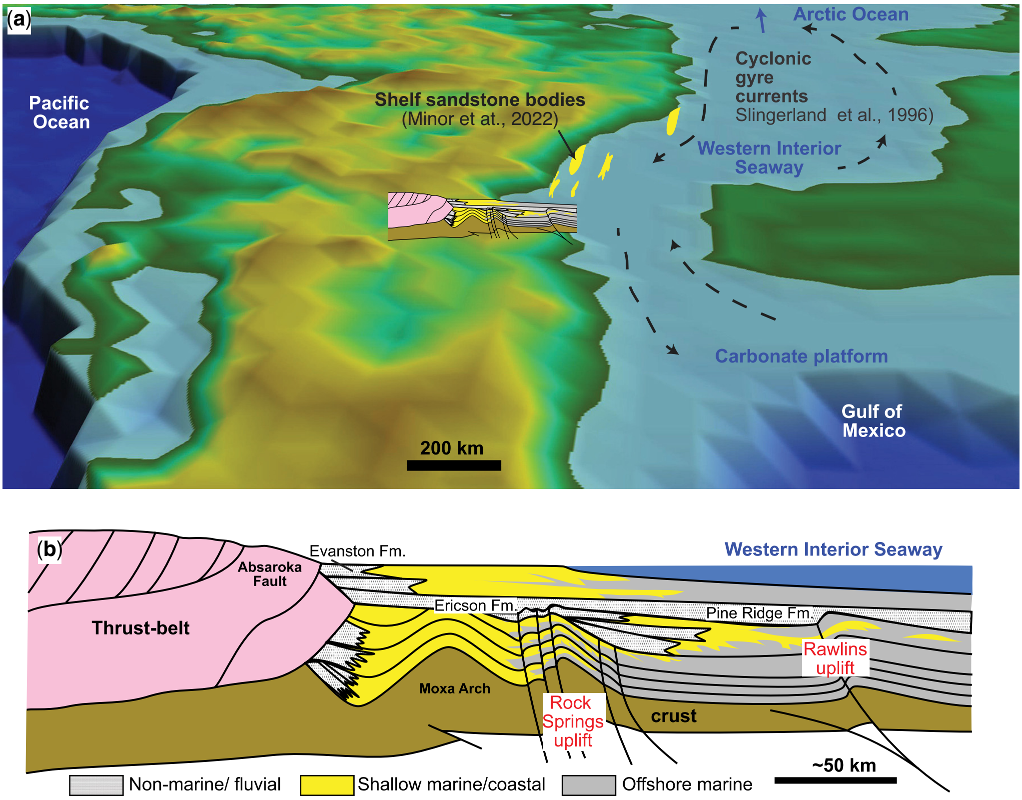

Fig. 14. (**a**) Palaeogeographical reconstruction of the Western Interior Seaway during the Campanian. (**b**) Cross-section of the western margin of the Western Interior Seaway from the thrust belt to the seaway, showing the outbuilding of several clastic wedges.

outbuilding of the seaway margins over several regressive and transgressive cycles (Fig. 14). This outbuilding from the margins represents the dominant process in seaways. In relatively shallow seaways, like the Cretaceous Western Interior Seaway, shorelines can migrate across the seaway for hundreds of kilometres, producing a sequence of clastic wedges composed of alluvial, coastal and marine depositional environments (Roehler 1990; Devlin *et al.* 1993; Gomez-Veroiza and Steel 2010; Steel *et al.* 2012; Leva López and Steel 2015; Minor *et al.* 2021). The wedges developed over timescales of millions of years, whereas the shorelines migrated back and forth on a scale of a few 100 kyr (Gomez-Veroiza and Steel 2010; Steel *et al.* 2012). During regressive phases alluvial and deltaic systems advance into the basin, whereas during transgressive phases estuaries and back-barrier-lagoonal deposits predominate. Along such wide margins, tidal currents can also flow perpendicularly to the coast, as previously discussed, producing classical tide-dominated or tide-influenced deltas and estuaries (see for example Steel *et al.* 2012; van Cappelle *et al.* 2016). A similar development has been recognized in the Mesozoic Laurasian Seaway, where a series of regressive-to-transgressive clastic wedges built out into the seaway from the Norwegian, Scottish and Greenland hinterlands on a scale of millions of years (Surlyk 1991; Partington *et al.* 1993; Steel 1993; Surlyk *et al.* 2021; Folkestad and Steel 2022). That is not to say there are not deltas prograding into straits, especially when the strait is bounded by high relief (such as Fraser Delta building into Georgia Strait in Canada, Mathews and Shepard 1962), but these deltas are not building considerable shelf-slope morphologies and the sediments are likely swept aside by the strait current circulation (Rossi *et al.* 2017).

If a seaway is deep enough and there is enough sediment supply, shelf-margin clinoforms can develop. This is readily visible in the modern Makassar Strait (notice Makassar is named a strait according to modern geography, but as we discussed previously (see Fig. 2) it has morphological characteristics and stratigraphy typical of seaways), where the Holocene evolution of the shelf margin stratigraphy is well-imaged with seismic data (Roberts and Sydow 2003). A well-defined shelf-margin clinoform advances into the *c.* 200 km wide Makassar Strait, reaching depths of *c.* 2000 m, and its topset stratigraphy is characterized by cross-shelf transits of the ancestral Mahakam River delta interfingering and alternating with bioherms (Roberts and Sydow 2003), but deltaic complexes have been advancing in the basin since the early Miocene (Storms *et al.* 2005).

Discussion

As previously noted, geographical names do not differentiate passageways based on the differences in their dimensions (e.g. narrow or wide, shallow or deep) and geological duration. However, in geology, this distinction might indeed be useful, as it results in depositional systems and stratigraphy built under different oceanographic conditions and preserves distinct sedimentary features.

We suggest that in general terms, the end-member *strait* is a connection between water bodies with relatively narrow width (i.e. from a few to *c.* 100 km; see again Fig. 4), and a geologically short temporal span (i.e. from 0.1 to typically less than 10 Ma; Fig. 4), as inferred from the reconstructed geological history of ancient straits. Straits have variable widths and depths (see also the review by Dalrymple 2022), and they focus water masses generating stronger currents than in the basins at their ends. It is common, but not always the case (see Dalrymple 2022), for straits to be linked to active tectonics, that in places or at given times during their evolution may create high accommodation for thick sequences and high-energy deposits dominated by cross-bedded, coarse-grained sediment. The high energy and coarser deposits of straits are key recognition criteria and are emphasized by comparisons with adjacent deposits that transition toward deeper or more distal parts of the basins (Fig. 12). We recognize the transient nature of the deposits and the strait basin itself, as not all deposits are coarse grained cross-strata because conditions change with sea-level and cross-sectional area morphology.

Straits may segment seaways or marine basins, control endemic species occurrence and presently they are heavily engineered and are prone to significant geohazards (e.g. Gofas 1998; Barrie *et al.* 2005).

The end-member *seaways* are also mostly tectonically formed, but represent wide basins (i.e. from hundreds up to *c.* 1000 km in width; Fig. 4) that connect with larger and deeper basins at their ends, and are likely to persist for long geological times (i.e. from tens to hundreds of millions of years; Fig. 4), as inferred from their geological history. Seaways are therefore large physiographic units that in places may contain even narrower water constrictions forming straits. Because of their usually large size, larger waves, complex water circulation, oceanic currents' influence and the Coriolis Effect are more common and trigger higher sedimentary process variability. Seaways are regionally, and sometimes globally, important from a palaeogeographical, palaeoceanographic and palaeoclimate point of view, and their opening or closure is a major environmental change bearing long-lasting effects.

The stratigraphic signature of the two end members strait and seaway is expected to be different, allowing their distinction in the rock record. From a stratigraphic and sedimentological point of view, a strait is a specific depositional system (see also Longhitano and Chiarella 2020; Dalrymple 2022) while a seaway represents a spatially larger and with longer life span system, composed of multiple coeval depositional systems, from fluvial to deep-marine that at times might include straits.

Possible modern analogues of the strait end member are the Bonifacio Strait (between Sardinia and Corsica in the Mediterranean Sea; Fig. 1b), the Jeju Strait (Korea), the Dover Strait (Fig. 1b) or the Straits of Mackinac. Possible analogues of the seaway end member are the Mozambique Channel (Fig. 1c), Baffin Seaway (Fig. 1a) and the Drake Passage, very different in size and depths but all connecting large water bodies for a long geological time. Nonetheless, it is important to remember that what we see in the modern geography is just a snapshot in time, whereas through geological time the dimensions and processes are constantly changing.

It is important to recognize that there is a natural continuum between straits and seaways, and we consider straits and seaways as the end members of the full spectrum of basin connections that can exist in nature. An example of the natural continuum between straits and seaways, highlighting the inherent complexity of these systems and the great variability that exists, is the evolution of the connection between the Atlantic Ocean and the Tethys–Mediterranean (Fig. 15). The connection between the Tethys and the Atlantic Ocean existed as a seaway since at least the Middle Eocene (Meulenkamp and Sissingh 2003). However, as a consequence of plate convergence and subduction rollback, the seaway has been slowly narrowing (Meulenkamp and Sissingh 2003; Carminati *et al.* 2012). In the Miocene, a series of relatively short-lived straits including the Guadalhorce, Zagra (Puga-Bernabéu *et al.* 2022), Dehesas de Guadix, the North Betic straits (Martín *et al.* 2014), and the Rifian Corridor (Krijgsman *et al.* 1999; Beelen *et al.* 2022), formed a 'multiple' corridor system within the narrowing seaway, created in a flexural tectonic setting

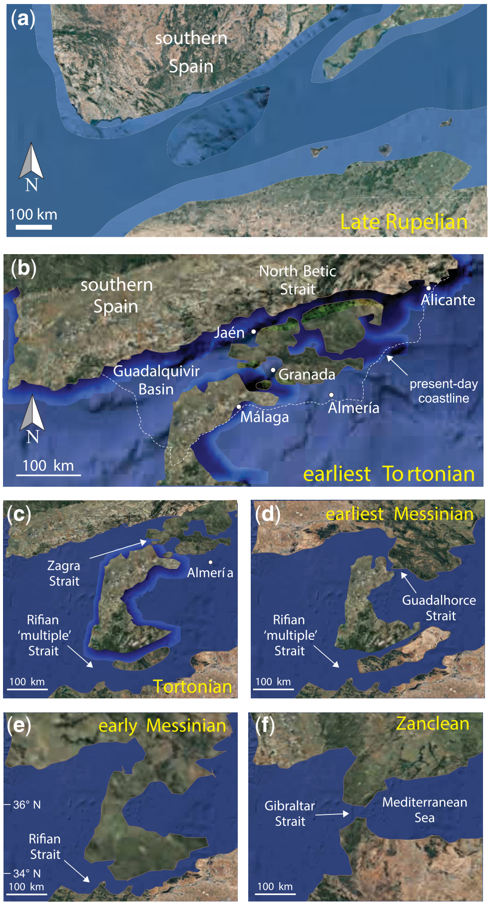

Fig. 15. Evolution of the Atlantic Ocean (to the west) and Tethys-Mediterranean (to the east) connection, from wide seaway (**a**) to a system of multiple straits that activated and deactivated during a time span of <3 Ma (**b–f**). Source: redrawn after Meulenkamp and Sissingh (2003) and Martín *et al.* (2014).

along the Betic Cordillera and the Rif Foreland (Fig. 15). The analysis of their rock record indicates several opening and closure phases during less than 3 Ma (Fig. 4), which had profound implications for Mediterranean waters restriction and stratification, and the initiation of the Messinian Salinity Crisis (Krijgsman *et al.* 1999; Martín *et al.* 2014). The compressional tectonics in the area caused the seaway to fragment into smaller straits, and as the tectonic activity continued, in conjunction with glacio-eustatic changes (Krijgsman *et al.* 1999), the connection between the Atlantic Ocean and the Mediterranean Sea narrowed into the modern Gibraltar Strait.

The continuum between straits and seaways can occur both in time (as highlighted above) and space (e.g. the great variability shown in Dalrymple 2022), giving rise to the occurrence of intermediate cases, with characteristics that are transitional between the two end-member cases. The English Channel, for example, is wide and characterized by currents flowing perpendicular to the margins, but it also characterized by coarse-grained axial facies due to flow amplification, and it is shallow enough to be exposed (i.e. shut down as a marine passageway) during low sea-level phases. The English Channel forms a spatial continuum with the Dover Strait. The modern Bonifacio Strait (Fig. 1b), while being unequivocally classified as a strait, has been active since the Langhian (Reynaud *et al.* 2013), that is for almost 16 Ma, falling in the uppermost range of strait duration, and having a time span that overlaps with the one typical of seaways, as discussed above (Fig. 4). However, we also note that throughout its evolution the Bonifacio Strait experienced several episodes of closure due to base level fall (during the Messinian Salinity Crisis and during the Quaternary glaciations; e.g. Reynaud *et al.* 2013). In some cases, straits may represent the initial stage of opening of an elongated-narrow basin that may later on evolve and expand into a wider seaway (and potentially evolving further into an ocean). This is particularly evident in the geological history of extensional settings (e.g. the proto-Atlantic seaways such as the Mesozoic Laurasian Seaway offshore Norway; see Folkestad and Steel 2022). This evolutionary transition from straits into seaways may also occur in reverse, when a seaway (sometimes originally an ocean, i.e. the Tethys Seaway) progressively shrinks into a narrower strait, the likelihood of which is higher in compressional settings (e.g. Fig. 15).

The distinction of the end members straits and seaways (and the intermediate cases in between them) has important implications for the correct interpretation of these systems in the rock record, to reconstruct the evolution of interconnected basins (e.g. Palcu and Krijgsman 2022), and to predict the occurrence and distribution of potential reservoirs and seals in the basin, both for conventional resources and CO_2 storage (e.g. Folkestad and Steel 2022; Meneguolo *et al.* 2022).

Conclusions

Straits and seaways are key connections between basins, regulating water, sediment and biota exchanges, and influencing local and global climate. However, their interpretation, even though fundamental for palaeogeographical and stratigraphic reconstructions, is not always straightforward.

Here, we suggest that straits and seaways are end members within a continuous spectrum with partly overlapping features, but nevertheless have some specific characteristics that can help to distinguish between them. This distinction is especially important to be made in the rock record:

(1) Straits and seaways develop over different (but partially overlapping) spatial and temporal scales. Duration v. width plot highlights that despite the continuum between straits and seaways, the two end-member groups can be separated. The end-member straits tend to have widths of the order of kilometres to tens of kilometres (up to 100 km), and durations of the order of tens of thousands to a few million years (up to a few tens of millions of years), whereas the end-member seaways tend to have widths of the order of hundreds to *c.* 1000 km, and a temporal span of several to hundreds of millions of years.

(2) The spatio-temporal differences between straits and seaways also affect the dominant oceanographic circulation. Straits are commonly characterized by strong flow convergence, turbulence and acceleration of water masses through one or multiple constrictions, so that the main current core flows parallel to the strait margins. Seaways are also characterized by water convergence due to the geographical narrowing, but no significant water turbulence occurs. Generally, the influence of waves and storm waves is stronger compared to strait settings, as well as the influence of the Coriolis effect, leading to more complex flows and process variability. Currents can flow parallel to the seaway axis, but the movement of currents perpendicular to the seaway margins is easier and more regionally widespread compared to straits.

(3) In a geological perspective, the end-member straits are therefore transitory features, mostly related to local tectonic settings that create conditions of lateral constrictions, whereas the end-member seaways persist for longer time and, especially large transcontinental ones, can connect oceans and basins from very different climatic zones, and can have a strong influence on global climate.

(4) The geological record of straits and seaways is expected to be different. Straits can be considered as individual depositional systems. One of their most diagnostic signatures in the rock record is the appearance in their infill of high-energy marine current facies such as vertically-stacked large-scale cross beds. High-energy facies and the general lack of mud in the deposits might dominate the entire stratigraphy, or might become recurrent as the depositional conditions vary. The dominant sediment transport and deposition in straits occur along predictable transport pathways, away from the zone(s) of velocity maxima. The grain-size trend therefore tends to increase in a margin-to-axis transect, but fines along the axis. Seaways resemble conditions most common to shelves, generally with a grain-size trend overall fining from the margins towards the basin axis. Seaways are composed of different depositional systems, from fluvial to deep-marine (and they can also include straits). Their stratigraphic architecture reflects the dominant process of outbuilding of the seaway margins over several millions of years, through multiple regressive and transgressive cycles, either as clastic wedges or as shelf-margin clinoforms.

We wish to emphasize that there is a natural continuum between straits and seaways, both in time and in space, and that the two should be regarded as end-member cases. Intermediate cases would have characteristics that are transitional between the ones of the two end members listed above.

In some instances, especially in deep time where only parts of the systems might be preserved, the distinction could not be very clear. To add even more complexity to reconstructions, through geological time, dimensions and processes may change. This is why it is only the combination of different criteria that can help to interpret correctly these features.

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