

Origin and Geomorphic Characteristics of Ocean Basins

Peter T. Harris and Miles Macmillan-Lawler

Abstract The results of a multivariate classification of ocean basins is presented, based on an existing digital global map of seafloor features that are related to major phases of evolution, namely young, mature, declining and terminal evolutionary stages. “Young” basins are characterised by the absence of ocean trenches, young ocean crust (<8 MA), large areas of continental slope, thick sediments, and large percentage area of mid-ocean ridge rift valley (above 1.7%). “Mature” ocean basins are characterised by relatively thick sediment deposits (mean of 940 m), large percentage areas of continental rise (mean of 19.8%) and large areas of submarine fans (mean of 4.3%). The area of ocean trench is relatively small in all “mature” ocean basins, ranging from 0 to 0.3%. A defining geomorphic feature of the “declining” category is that around 1% of their area is trench. “Declining” ocean basins contain the highest concentration of seamounts (3.5–5 seamounts per 100,000 km²), which is more than double the mean value (1.4 seamounts per 100,000 km²) that occurs for the “mature” category with the next highest concentration. The “terminal” category of ocean basins is characterised by the greatest mean sediment thickness (4311 m) and greatest percentage area of submarine fans (7.2%) of any ocean basin. Bottom water occurring within 33 major bathymetric basins (located within the broader ocean basins) is found to exhibit a spatial relationship to near-bottom dissolved oxygen (DO) concentrations. Gradients of decreasing DO concentration suggests bottom water pathways within basins and between adjacent basins of similar (or greater) depth.

1 Introduction

Studies of seafloor geomorphology have expanded in recent years with the advent of new technologies and new methods that have revealed the true shape of the ocean floor, which lies otherwise hidden beneath kilometres of ocean (Hillier et al.

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2008). These methods include new swath sonar seafloor mapping technologies (see Chapters “[Sidescan Sonar](#)”, “[Multibeam Echosounders](#)” and “[Quantitative Analyses of Morphological Data](#)” of this volume), but also new global compilations of digital bathymetry compiled from sonar and satellite altimetry data (Smith and Sandwell 1997; Becker et al. 2009). Such global compilations of bathymetric data permit global assessments of different categories of seafloor geomorphic features, examples being seamounts (Wessel 2001; Hillier and Watts 2007; Yesson et al. 2011), trenches (Jamieson et al. 2010) and submarine canyons (Harris and Whiteway 2011), but also integrated assessments of global seafloor geomorphology (Harris et al. 2014). From such compilations it is now possible, for the first time, to examine global patterns of categories of seafloor features mapped digitally, individually or as assemblages, using quantitative and statistical methods and to relate them to the formative processes. It is, indeed, the dawning of a new era in the study of the geomorphology of the oceans (Hillier et al. 2008).

This chapter contributes to previous global studies of ocean geomorphology to examine the evolution of ocean basins, from their youth through their old age and demise, in terms of the geomorphic characteristics that define them at each evolutionary stage. A second, related topic is the control that seafloor geomorphology exerts on the circulation of bottom water within and between ocean basins. The purpose of this work is to reveal interlinkages between geomorphic form and process, through the examination of basin evolution and water circulation at a global spatial scale.

1.1 Definition of Terms—Ocean Basins and Bathymetric Basins

The earth’s ocean basins are comprised of all the seafloor features that are apart from the continents; they comprise that part of the earth’s surface that is composed primarily of basaltic, ocean crust, in contrast with the mainly granitic, continental crust forming the continents. The transition from basaltic, ocean crust, to granitic, continental crust occurs within the continental slope. If the boundary of ocean basins is taken as the continental shelf-break, then the continental slope is also included within ocean basins (i.e. only the continental shelf is excluded). In this broad definition, ocean basins cover approximately 329,640,970 km² or about 65% of the earth’s surface.¹ They contain all of the mid-ocean ridges, abyssal hills and mountains, abyssal plains, seamounts, troughs, trenches, plateaus, slope-incising

¹Although the oceans are commonly stated as covering 72% of the earth, this figure includes the (submerged) continental shelves, which are geologically extensions of the continents and not part of the ocean basins. Continental shelves cover an area of 32,242,540 km² or 8.91% of the oceans (Harris et al. 2014).

submarine canyons, fans, continental rise and the numerous other features found in the deep ocean.

There are, furthermore, smaller bathymetric basins nested within the more broadly defined ocean basins. According to the International Hydrographic Organization, a bathymetric basin is “a depression, in the sea floor, more or less equidimensional in plan and of variable extent” (IHO 2008). The largest bathymetric basins of the major oceans are nominally bounded by the foot of slope and by the mid-ocean spreading ridges (Wright and Rothery 1998; Gille et al. 2004). Bathymetric basins can be mapped based on the identification of the most shoal, closed, bathymetric contours, examined regionally for the major ocean basins and shelf seas. In addition, numerous smaller basins of the bathyal and hadal zones, located outside of the major ocean basin areas, occur, identified by their most shoal, closed, bathymetric contours. Tracking the flow of dense, bottom water formed in the oceans is linked to the spatial distribution of bathymetric basins, because such dense water is transported into basins by gravity. At abyssal depths, using this approach, Harris et al. (2014) distinguished between 33 major bathymetric basins having a mean size of 3.8 million km², 1917 large bathymetric basins (>800 km²), and 4520 small bathymetric basins (<800 km²). A further 1507 bathymetric basins were mapped, perched on the continental slope.

Bathymetric (geomorphic) basins are not to be confused with sedimentary basins studied by geologists and stratigraphers. Sedimentary basins are regions commonly located along continental margins where long-term subsidence creates accommodation space for infilling by sediments. They do not necessarily exhibit the surface expression of a “bathymetric basin” as defined above.

Bathymetric basins (depressions) perched on the continental shelf and slope, are not the main subject of this chapter. Shelf-perched basins are most common on glaciated continental margins where glacial erosion has excavated a trough on the continental shelf. Tectonic rifting, volcanism, gas escape and other processes may also give rise to the formation of localised depressions and small basins perched on the continental shelf and slope.

1.2 Tectonic Origin of Ocean Basins

Ocean basins are ultimately the product of rifting of ocean crust, seafloor spreading followed by subduction and destruction of ocean crust (Hess 1962), giving rise to the so-called Wilson Cycle (Wilson 1966; Fig. 1). The Wilson Cycle is initiated where upwelling of mantle magma causes a rifting of continental crust; the great rift valley of east Africa is an example (Baker et al. 1972). The rift opens and becomes flooded with seawater, forming a new arm of the ocean. The Red Sea and Gulf of California are examples (Table 1). Next comes the establishment of mid-ocean spreading ridges, seafloor spreading and the formation of ocean crust at which stage the ocean basin has reached a mature stage (e.g. the North and South Atlantic Oceans). This is followed by the formation of subduction zones and ocean trench

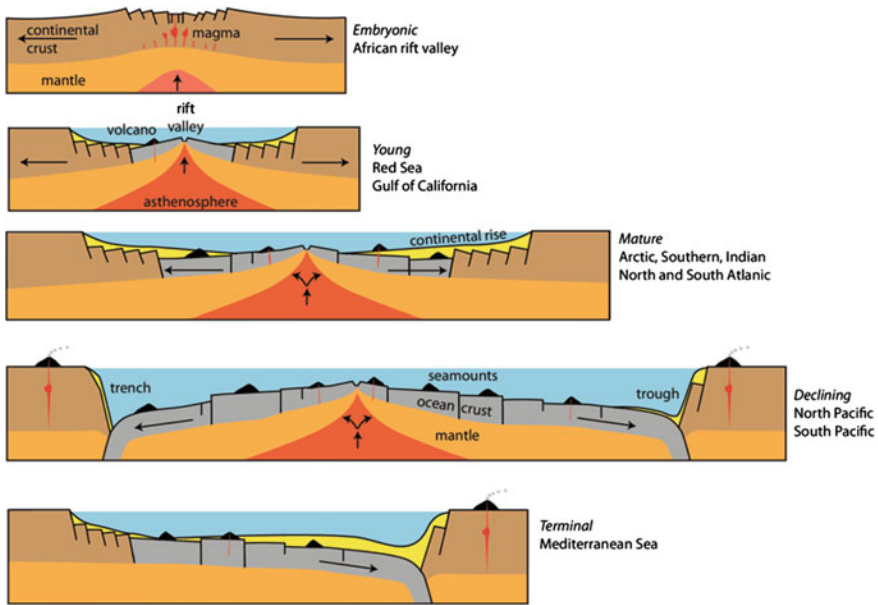


Fig. 1 Wilson Cycle (Wilson 1966) of ocean basin evolution

Table 1 Evolution of ocean basins (Wilson Cycle), from rifting to terminal phase (adapted from Wright and Rothery 1998)

Stage	Examples	Dominant tectonic motions	Characteristic geomorphic features
1. Embryonic	East African rift valleys	Crustal extension and uplift	Rift valleys
2. Young	Red Sea	Subsidence and spreading	Narrow seas with parallel coasts and central depression
3. Mature	Atlantic Ocean	Spreading	Ocean basin with active mid-ocean ridge
4. Declining	Pacific Ocean	Spreading and subduction (active margins)	Ocean basin with active mid-ocean ridge; island arcs; trenches along most margins
5. Terminal	Mediterranean Sea	Subduction and uplift	Young mountains

systems, whereby the basin enters a declining phase (e.g. the North and South Pacific Oceans). Eventually the rate at which ocean crust is destroyed in subduction zones exceeds the rate at which it is formed at spreading ridges. The basin thus becomes dominated by the subduction process and shrinks in area. Finally it enters its terminal phase, an example being the Mediterranean Sea (Table 1).

The applicability of the Wilson Cycle model for understanding the evolution of ocean basins has been documented in the geologic record with regards to the

formation, growth and demise of the Tethys Ocean (Ricou 1996; Stow 2010). This ocean basin is thought to have been initiated prior to the Permian and became a mature basin as a “C” shaped indentation along the eastern, equatorial coast of Pangea during the Late Permian (260 MA). Tethys transformed from a mature ocean basin into a declining basin during the Cretaceous, at which time it occupied a space between the continents of Gondwana and Laurasia. As tectonic forces moved the continental plates over geologic time, the Tethys Ocean became squeezed into a seaway confined between Africa and Eurasia by the Eocene. It ceased to exist as an ocean by around 6 MA and it is now in its final, terminal phase, represented by the Mediterranean Sea.

1.3 Multiple Origins of Bathymetric Ocean Basins

Declining and mature ocean basins (Table 1) have an asymmetric bathymetric profile with their deepest parts adjacent to continents (with declining basins containing trenches or troughs) gently shoaling towards the mid-ocean spreading ridge. Hence the bathymetric ocean basins commonly have the mid-ocean spreading ridges as one of their boundaries and continental landmasses as the other. Such basins have been termed *thalassogens* by Pushcharovsky (2006).

After ocean crust is formed at mid-ocean spreading ridges, it is transported laterally away from the spreading ridge where it gradually cools and subsides. It has been shown (e.g. Hillier and Watts 2005) that the rate of subsidence generally adheres to the infinite half-space model between change in seafloor depth Δh (km) and the age of ocean crust t (MA), given as:

$$\Delta h = C(t)^{1/2}, \quad (1)$$

where C is an empirically defined coefficient (m), given as 307 by Hillier and Watts (2005) for $t < 80$ MA. The infinite half-space model holds true for ocean crust flanking the mid-ocean spreading ridges, but it is not universal because factors other than ageing and cooling play a role in ocean crust subsidence. Such factors include volcanism, tectonic rifting, isostasy, etc. and these may cause lateral variations in the rate of subsidence and hence result in the formation of localised bathymetric basins (Hillier and Watts 2005; Pushcharovsky 2006). Consequently, there are different types of bathymetric basins. Two examples are those that are formed by raised ocean crust associated with chains of volcanos, which have been termed *intermontane* basins, and those formed by tectonic rifting and fracturing of ocean crust, which have been termed *interfault* basins (Pushcharovsky 2006).

An example of an *intermontane* bathymetric basin is the Kamehameha Basin in the central Pacific. This basin is formed as a seafloor depression surrounded by zones of numerous seamounts and ridge complexes on its southern and western

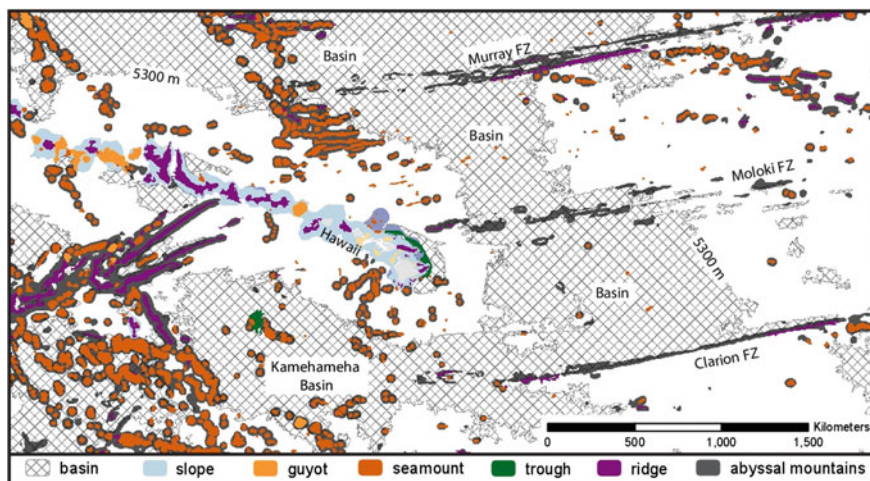


Fig. 2 Map of selected seafloor geomorphic features from the global seafloor features map; see Harris et al. (2014) for definitions of features and methods used to map them

margins with the Hawaiian archipelago forming the northern and eastern boundaries (Fig. 2). The Kamehameha Basin is delimited by the 5300 m depth contour and it is connected to other basins located further east (Fig. 2).

Examples of *interfault* basins are those located between the major fracture zones of the northeast Pacific (i.e. the Clipperton, Clarion, Moloki, Murray and Mendocino Fracture Zones). These bathymetric basins are also delimited by the 5300 m depth contour, which is clearly deflected along the Clarion, Moloki and Murray fracture zones (Fig. 2) by their positive relief. The basin complex is partially confined by the fracture zones along their northern and southern margins, although the regional basin complex is interconnected (at a depth of 5300 m).

1.4 Aims of This Study

The tectonic processes governing the evolution of ocean basins (Wilson Cycle) give rise to different assemblages of geomorphic features as they pass through the different stages of evolution (i.e. from embryonic to terminal stages; Table 1). These features include rift valleys, spreading ridges and ocean trenches, but it is apparent that other processes, specifically volcanism and sedimentation, play a role in basin evolution. These processes, in turn, influence the nature of geomorphic features that characterise ocean basins at different stages of their evolution. Although we have a broad conceptual model on the stages of ocean basin evolution (Fig. 1), a

quantitative assessment of geomorphic features that characterise ocean basins at different stages of their evolution has not previously been completed. Here, we analyse a recently published geomorphic features map of the global ocean (Harris et al. 2014) in order to fill this knowledge gap. The aim of this study is to identify and document changes in the composition of geomorphic features that characterise the earth's ocean basins as they evolve from embryonic to terminal stages of evolution according to the Wilson Cycle.

2 Methods

Our analysis includes a classification of ocean basins using hierarchical clustering in the R statistical package. The first step in our analysis was to divide the oceans into areas consistent with the evolutionary processes described above (Table 1) and based on the IHO Sea Area definitions.² Hence the ocean areas considered are: Red Sea; Gulf of California; Arctic Ocean; Southern Ocean; Indian Ocean; South Atlantic Ocean; North Atlantic Ocean; South Pacific Ocean; North Pacific Ocean; and the Mediterranean Sea (Fig. 3). For the purpose of this analysis the shelf regions and their associated features were removed and only those features occurring on the continental slope and at abyssal to hadal depths were considered.

The next step was to define input data to be used in the clustering analysis. We used geomorphic feature statistics based on the mapped surface areas of geomorphic features reported by Harris et al. (2014), who describe the methods used to map 29 seafloor feature types in the global ocean. Only those features that occur seaward of the shelf break were used in the present study, resulting in the inclusion of 24 of the 29 feature categories mapped by Harris et al. (2014). All 24 features were examined for correlations with ocean age (mean and maximum) and trench area using the 'cor' function in the R statistical package. The following variables were used: % (percentage area of) continental slope; % abyssal plains; % hadal area; % bathymetric basin; % submarine fan; % seamount; % ridge; % rift valley; % continental rise; and % spreading ridge.

In addition to geomorphic feature statistics, we used the global sediment thickness map of Divins (2003), the average rate of seafloor spreading and age of ocean crust calculated using digital isochrones of Muller et al. (1997) to derive an average spreading rate, age-range and mean age for each ocean basin.

Clustering was carried out using the 'hclust' hierarchical clustering algorithm in the R statistical package based on the mean values for the geomorphic features and other basin values defined above (Table 2).

²VLIZ (2005). IHO Sea Areas. Available online at <http://www.marineregions.org/>. Consulted on 2016-04-04.

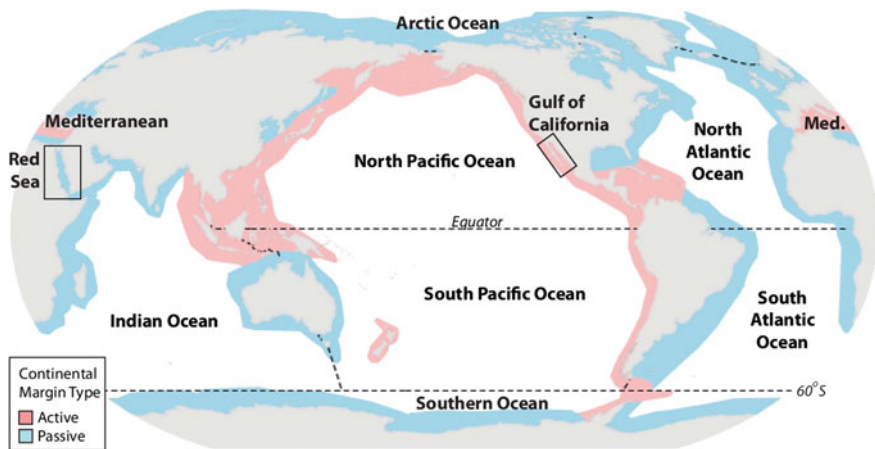


Fig. 3 Ocean basins used in the analysis; the areas of passive and active continental margins are indicated

3 Results

Clustering using the input data listed in Table 2 placed each of the 10 defined ocean areas into four separate categories (young; mature; declining; terminal; Figs. 1 and 4). The young category includes the Gulf of California and the Red Sea (Fig. 5). These relatively small ocean areas are characterised by the absence of ocean trenches and hadal depth ocean floor, young ocean crust (<8 MA), comparatively large areas of continental slope (33–75% slope for the Gulf of California and the Red Sea, respectively), thick sediments, small areas of abyssal plains and a relatively large percent area of mid-ocean ridge rift valley (above 1.7%). The area of submarine canyons in all ocean basins (Table 3) is correlated with the area of slope ($r = 0.80$), and therefore the area of canyons is also relatively greater in young ocean basins.

The mature category includes 5 major oceans (Fig. 4), listed here in order of increasing percentage area of ocean trench: Arctic (Fig. 6a); Southern; Indian; South Atlantic and North Atlantic (Fig. 6b). The area of ocean trench is relatively small in all mature ocean basins compared with declining and terminal basins, ranging from 0 to 0.3% (Table 2). The mean age of ocean crust in these basins is 65 MA and the mean maximum age is 160 MA. These are comparable values to the two declining ocean basins but much greater than the young basins and much younger than the terminal Mediterranean Sea. The mature ocean basins have a mean mid-ocean ridge spreading rate of 28.6 mm/year, which is comparable to the approximate spreading rates reported for the young ocean basins but only about half the speed of the two declining ocean basins (which average 58 mm/year). From a

Table 2 Statistics on variables used in clustering ocean basins into one of the four evolutionary categories

Stage	Ocean basin name	Trench (%)	Age mean (MA)	Age max (MA)	Sediment thickness (m)	Spreading rate mm/year	Slope (%)	Abyssal plains (%)	Hadal (%)	Bathymetric basin (%)	Fan (%)	Seamount (%)	Seamounts per 10 ⁵ km ²	Ridge (%)	Rift valley (%)	Rise (%)	Spreading ridge (%)
Young	Red sea	0	0	0	1248	10	33.3	11.5	0	96.5	0	0	0	0	4.5	0	0
	Gulf of California	0	1	8	357	43	74.9	3.6	0	16.7	0.9	0.5	0.9	0	1.7	0	0.5
Mature	Arctic Ocean	0	69	159	854	31	14.6	33	0	46.4	2.4	0.1	0.123	1.9	0.5	14.5	4
	Southern Ocean	0.04	70	160	984	27	3.5	48.6	0.01	54.2	6.6	0.9	1.24	1.8	0.1	38.1	1.9
	Indian Ocean	0.2	55	159	703	40	6.1	32.5	0.4	48.7	6.5	1.4	1.56	2.5	0.2	9.3	2.3
	South Atlantic Ocean	0.2	57	139	722	26	4.1	26.1	0.5	46.7	2.3	2.1	2.46	2.8	0.3	16.2	3
Declining	North Atlantic Ocean	0.3	74	180	1442	19	9.2	27.4	0.8	45.1	3.5	1.4	1.74	2.6	0.3	20.9	1.8
	South Pacific Ocean	0.9	47	152	229	58	3.8	26.8	0.5	46.5	0.03	2.8	3.49	3	0.2	0.7	2.2
Terminal	North Pacific Ocean	1.1	79	175	386	57	6.2	32.9	3	44.6	0.3	4.1	4.95	3.7	0.1	1.3	1.1
	Med. Sea	0.6	186	278	4311	29	39.2	26.5	0	69.7	7.2	0.3	0.827	1.1	0	16.6	0

Data on mean crustal age and spreading rates are from Muller et al. (1997). Sediment thickness data are taken from Divins (2003) and Backman et al. (2004). Data on geomorphic features are from Harris et al. (2014)

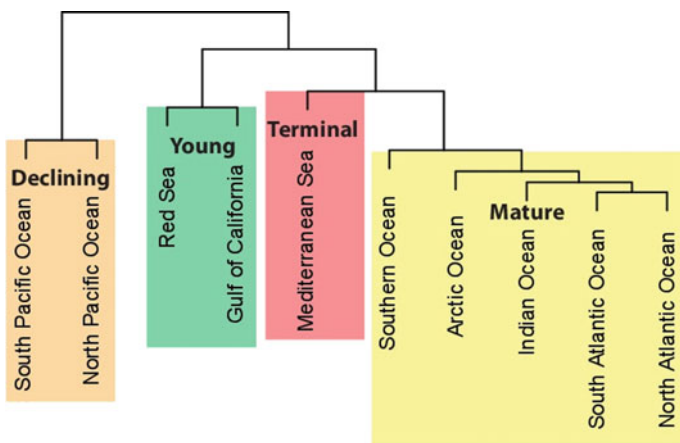


Fig. 4 Results of cluster analysis derived using the 'hclust' hierarchical clustering algorithm in the R statistical package based on the mean values for the geomorphic features (listed in Table 2)

geomorphic feature perspective, the mature ocean basins are characterised by relatively large percentage areas of continental rise (mean of 19.8%) and submarine fans (mean of 4.3%), which is consistent with the relatively thick sediments deposited in these basins (mean thickness of 940 m).

The declining category includes 2 major oceans (the North and South Pacific; Fig. 7) which together cover 169,056,690 km² equal to 47% of the global ocean. A defining geomorphic feature of the declining category is that around 1% of their area is trench. This is more than twice the area of trenches contained in the other categories. Another characteristic is the rapid mid-ocean ridge mean spreading rate of 57–58 mm/year. The thin nature of sediment deposits (mean thickness of about 300 m) is also a characteristic of the declining category, which is consistent with its relatively small percentage areas of continental rise (about 1%) and submarine fans (0.03–0.3%). Finally, the declining ocean basins contain the highest concentration of seamounts (3.5–5 seamounts per 100,000 km²), which is more than double the mean value (1.4 seamounts per 100,000 km²) that occurs for the mature category with the next highest concentration.

The terminal category of ocean basins is represented only by the Mediterranean Sea (Fig. 8). It is characterised by the greatest mean and maximum ages of ocean crust (186 and 278 MA, respectively) which is more than twice the ages of the mature and declining categories. The terminal category is also characterised by the greatest mean sediment thickness (4311 m) and greatest percentage area of submarine fans (7.2%) of any ocean basin.

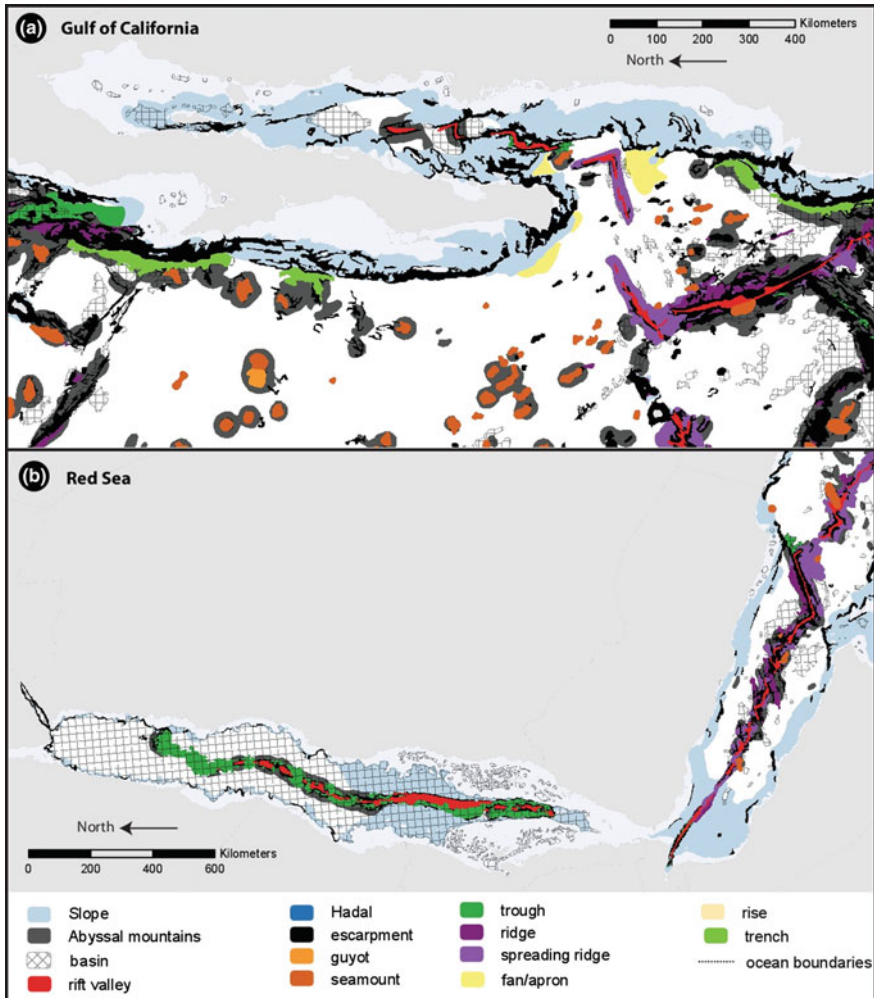


Fig. 5 Maps of selected geomorphic features from the global seafloor features map of Harris et al. (2014), illustrating examples of young ocean basins: **a** Gulf of California; and **b** the Red Sea

4 Discussion

4.1 Key Drivers of Basin Evolution

Based on the review presented above, it is apparent that the fundamental, main drivers of basin geomorphic evolution are tectonism, volcanism and sedimentation. Tectonism is the process which gives rise to the basin in the first instance and which governs its progress through the evolutionary Wilson Cycle, culminating in its ultimate destruction via subduction (Fig. 1). A principle geomorphic expression of

Table 3 Statistics on variables not used in clustering ocean basins into one of the four evolutionary categories

Stage	Ocean basin name	Trough (%)	Abyssal (%)	Escarpments (%)	Canyons (%)	Plateaus (%)	Abyssal hills (%)	Abyssal Mts (%)	Terraces (%)	Active margin (%)
Young	Red Sea	20	66.7	7.2	1.30	0	42.2	13	12	0
	Gulf of California	2.4	25.1	17.9	8.80	0	14.4	7.2	2.7	(100)
Mature	Arctic Ocean	0.7	85.4	3.3	5.70	19	35.8	16.5	3.6	0
	Southern Ocean	0.5	96.5	3.7	3.10	2.6	38	9.9	0.2	16
	Indian Ocean	0.5	93.5	4.8	1.10	7.1	44.9	16.2	1.2	36
	South Atlantic Ocean	0.4	95.3	5.0	0.80	3.1	50.8	18.3	0.7	2
	North Atlantic Ocean	0.8	90	7.3	2.00	4.3	44	18.6	0.9	37
Declining	South Pacific Ocean	0.8	90.8	8.5	1.10	2.4	39.2	18.7	0.4	84
	North Pacific Ocean	1.3	95.8	6.6	0.80	8.1	52.1	16.9	0.2	96
Terminal	Med. Sea	2.8	60.8	10.5	7.00	0	26.5	7.7	2.2	76

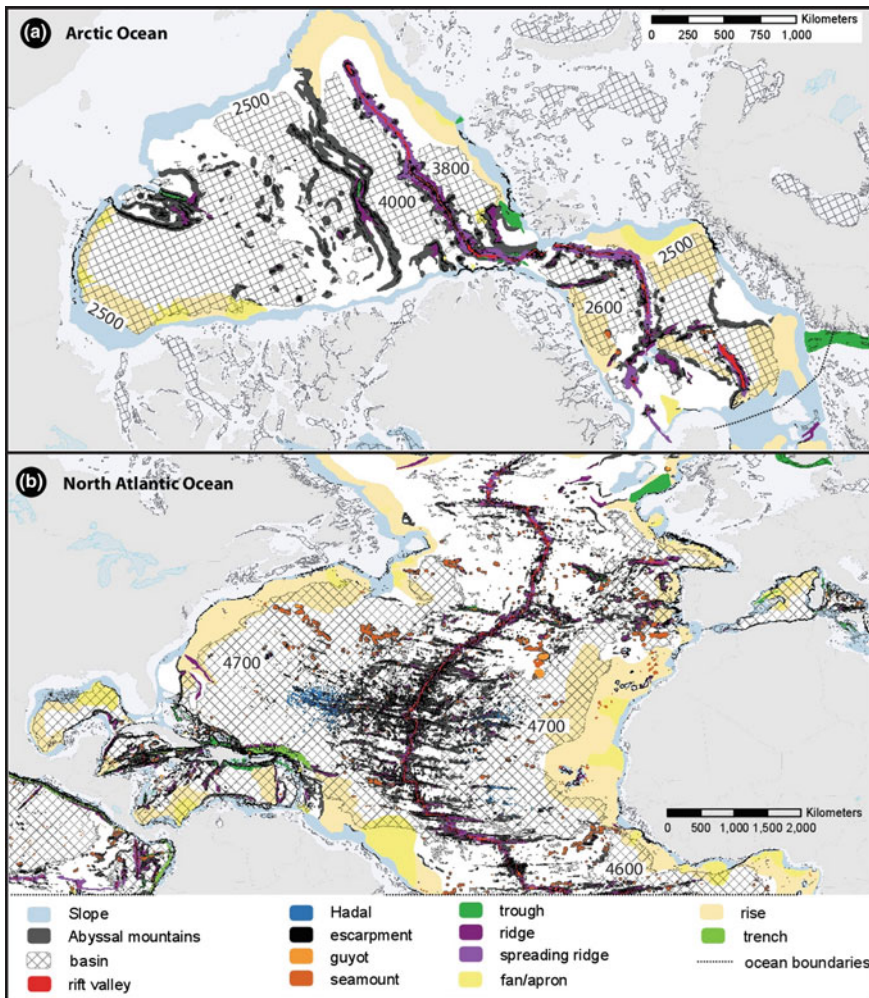


Fig. 6 Maps of selected geomorphic features from the global seafloor features map of Harris et al. (2014), illustrating examples of mature ocean basins: **a** Arctic Ocean; and **b** North Atlantic Ocean. The Arctic Ocean is the youngest of the “mature” ocean basins, relatively small in size and characterised by the absence of trenches, its large areas of slope and large areas of submarine canyons. In contrast the North Atlantic exhibits some trench areas (the Puerto Rico Trench) along its small length of active margin

tectonism that characterises ocean basins as they progress through the Wilson Cycle is the percentage area of deep ocean trench, reflecting the subduction of oceanic crust (Table 2) along active margins (Table 3; Fig. 3). Trench area is correlated with the area of troughs in mature and declining ocean basins ($r = 0.81$). This is explained by the fact that troughs are sometimes trenches that have been partially infilled with sediment. In mature and declining ocean basins, the percentage area of

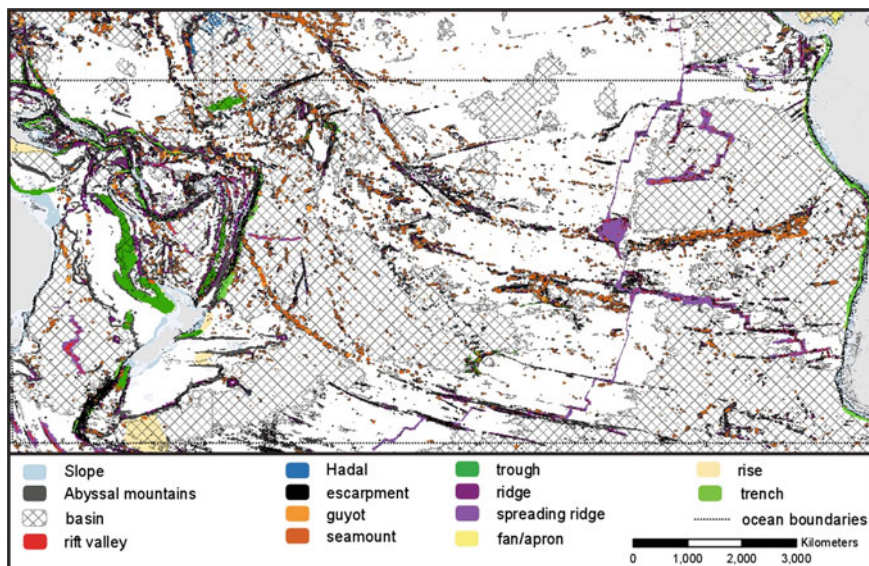


Fig. 7 Map of selected geomorphic features from the global seafloor features map of Harris et al. (2014), illustrating the “declining” South Pacific Ocean basin. A defining geomorphic feature of the “declining” category is that around 1% of their area is trench, which is more than twice the area of trenches contained in the other categories. “Declining” ocean basins contain the highest concentration of seamounts (3.5–5 seamounts per 100,000 km²), which is more than double the mean value (1.4 seamounts per 100,000 km²) that occurs for the “mature” category with the next highest concentration

the steepest ocean floor (represented by escarpments) is positively correlated with trenches ($r = 0.77$) and steep-sided features such as ridges ($r = 0.72$) and seamounts ($r = 0.69$). Thus, as the ocean basin evolves from a mature phase and enters a declining phase, the percentage areas of trenches, troughs, ridges, seamounts and escarpments reaches a peak.

By contrast, the percentage area of the continental slope is inversely related to the occurrence of subduction zones along active margins. The percentage area of slope attains its maximum in the youthful and terminal stages of basin evolution. Slope area is also associated with the relative volume of sediment deposited in basins having passive margins, as discussed below.

The geomorphic expression of volcanism is manifest as the occurrence of mid-ocean spreading ridges, their associated rift valleys and seamounts. Young ocean basins are characterised by large percentage areas of rift valley (1.7 and 4.5% of the basin area for the Gulf of California and Red Sea, respectively) whereas mature ocean basins have the highest percentage area of spreading ridges (1.8–4% of basin area; Table 2). Seamounts are formed mainly along spreading ridges, proximal to the rift valley and located over the thinnest ocean crust (Wright and Rothery 1998; see also Chapters “Mid-Ocean Ridges” and “Cold Seep Systems” in

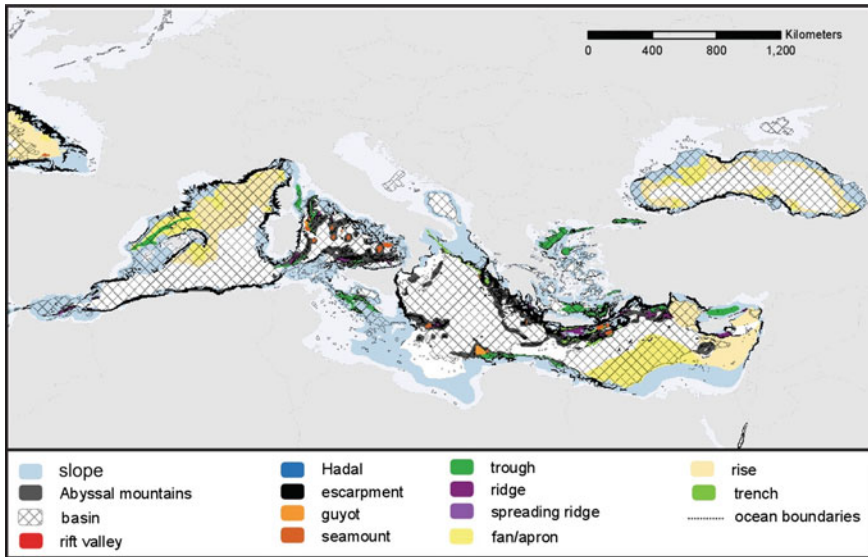


Fig. 8 Map of selected geomorphic features from the global seafloor features map of Harris et al. (2014), illustrating the “terminal” Mediterranean Sea basin. “Terminal” basins are characterized by the greatest mean sediment thickness (4311 m) and greatest percentage area of submarine fans (7.2%) of any ocean basin

this volume); seamounts appear to reach a maximum concentration (measured as seamounts per 100,000 km² of ocean basin) in declining ocean basins; possible explanations for this trend are discussed below.

Sedimentation also has a strong influence over the geomorphology of ocean basins at different stages of their evolution. In the youthful stage of basin evolution, sediments are transported into the basin forming thick deposits along the margins. In the Red Sea, sediments have a mean thickness of over 1200 m (Table 2), comprised of a Cenozoic evaporite succession laid-down during periods when the basin was episodically flooded and then cut-off from the adjacent ocean (Wright and Rothery 1998). Sediments extend across the full width of the basin and are reported from recent multibeam sonar surveys to be locally slumping into the central rift valley, forming bridges that separate deeper, isolated segments of the rift valley complex (Augustin et al. 2014). The same process of bridge formation by sediment slumping into the Mariana Trench has been described by Gardner and Armstrong (2011). This pattern of isolated segments of rift valley separated by bridges is detectable in maps of both the Gulf of California and the Red Sea (Fig. 5).

Mature ocean basins also contain thick sediment deposits along their (mainly) passive continental margins that attain mean thicknesses of between 700 to over 1400 m (Table 2). The geomorphic expression of these thick sediment deposits are large areas of continental rise (9–38% of basin area), large areas of submarine fans (2.3–6.6% of basin area) and a more subdued terrain, manifested as relatively small

areas of escarpment (generally less than 7% of basin area). In their analysis of the geomorphology of passive continental margins, O'Grady et al. (2000) reported that gently sloped margins tend to occur in regions with high sediment input, whereas higher gradient margins tend to have lower sediment input, which is consistent with the present interpretation of margin geomorphology.

When a basin enters its declining phase, the basin margins become dominated by a semi-continuous trench-trough system, created through the process of tectonic subduction of oceanic crust beneath continental crust. The trenches and troughs capture terrigenous sediments entering the basin sourced from the land, trapping them within the narrow subduction zone and inhibiting deposition seaward of the trench-trough system inside the basin. The result is that sediment deposits within declining ocean basins are very thin, attaining mean thicknesses of only 229 and 386 m in the South and North Pacific basins, respectively.

The transition from the mature to the declining evolutionary phase of ocean basins coincides with the basin margins changing from tectonically passive margins to active margins (Fig. 3). Another geomorphic signature of this transition from passive to active margins is the change in overall submarine canyon geomorphology (see Chap. 15 in this volume). Harris and Whiteway (2011) found that active continental margins contain 15% more canyons than passive margins and the canyons are steeper, shorter, more dendritic and more closely spaced on active than on passive continental margins. It was also found that river-associated, shelf-incising canyons are more numerous on active continental margins than on passive margins and that the occurrence of shelf-incising canyons is associated with the overall rate of sediment input (Harris and Whiteway 2011).

At locations where the rate of sediment influx into the trench-trough system exceeds the rate at which crust is subducted into the earth's mantle (i.e. where sediment influx rates are very high and/or where the rate of subduction is very slow) submarine fans and the development of a continental rise may occur along active plate margins. Such a pattern is manifest along the Pacific coast of California where the Pacific plate engages with the North American plate (Fig. 9); the boundary changes from mainly strike-slip between the Mendocino and Murray fracture zones to more complex movements that include partial subduction north of the Mendocino and south of the Murray fracture zones (Nicholson et al. 1994). In the mostly strike-slip region located between the Mendocino and Murray fracture zones, the absence of a trench-trough system has allowed sediments to be deposited along the margin to form a prograding continental rise, which is confined to the region between the two fracture zones (Fig. 9). To the south of the Murray fracture zone, offshore of southern California and Mexico, the plate motion is more complex and involves partial subduction as expressed geomorphologically by a very narrow continental slope, the occurrence of troughs adjacent to the foot of slope with a complex ridge and swale terrain further offshore (Fig. 9). To the north of the Mendocino fracture zone and offshore of the states of Washington and Oregon, the Cascadia (thrust-faulted) margin exhibits only localised submarine fan complexes (Nitinat and Astoria Fans; Atwater et al. 2014) and a continental rise has not developed (Fig. 9).

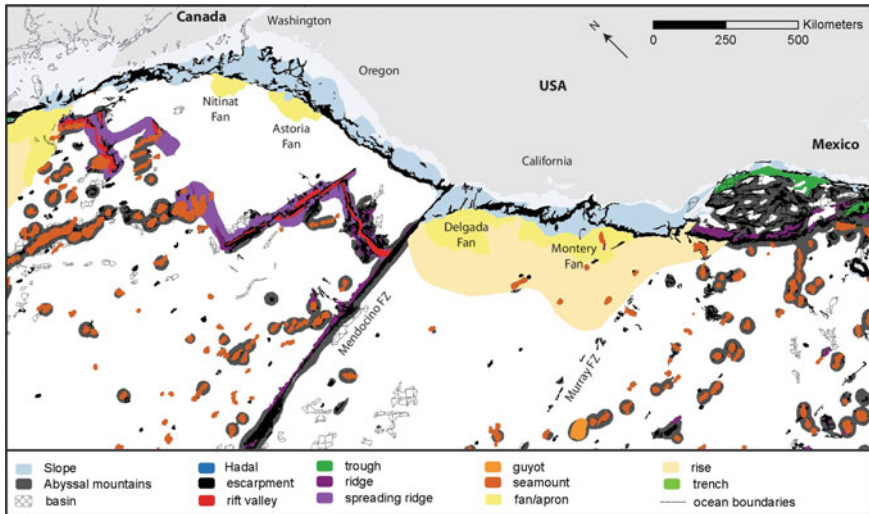


Fig. 9 Map of selected geomorphic features from the global seafloor features map of Harris et al. (2014), illustrating the relationship between the occurrence of continental rise with fracture zones along the western continental margin of California. Continental rise is developed between the Mendocino and Murray fracture zones (FZ) but does not occur to the north or south of this location; see text for explanation. The locations of submarine fans mentioned in the text are indicated

The Mediterranean Sea is the only example of the terminal phase of the Wilson Cycle and in this case the rate of sediment influx into the trench-trough system exceeds the rate at which ocean crust is subducted. This basin exhibits the greatest mean sediment thickness of any basin (mean thickness of 4311 m; Table 2).

4.2 *Seamount Frequency of Occurrence and Sediment Thickness*

An interesting pattern of seamount distribution in the oceans is their greater frequency of occurrence in declining ocean basins, compared with mature basins (e.g. Yesson et al. 2011; Table 2). Possible explanations for the differences in the spatial distribution pattern of seamounts across and between oceans could be possibly related to volcanic processes, such as temporal variability in the rate of volcanic eruptions along spreading ridges (Hillier and Watts 2007) or to differential burial of seamounts (Wright and Rothery 1998).

As noted above, the deposits of sediments in declining ocean basins are thin and patchy because land-derived sediments are intercepted and trapped by trench and trough systems located over the subduction zones of active continental margins. In contrast, the passive (trench-free) margins of mature ocean basins exhibit thick

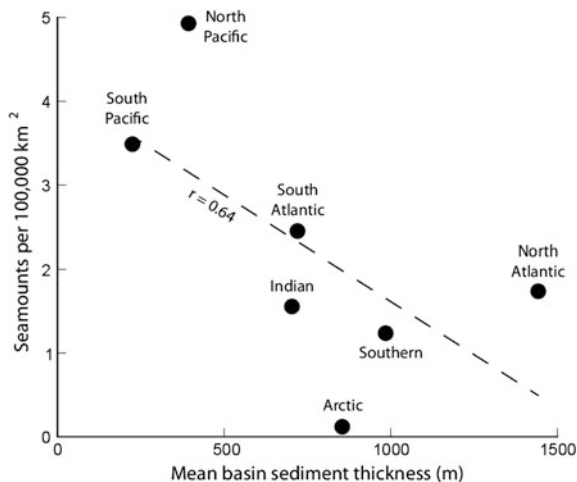


Fig. 10 Plot of mean seamount concentration (seamounts per 100,000 km²) versus mean sediment thickness in mature and declining ocean basins. The linear correlation coefficient (r) is indicated. Fig. 11 Bathymetric basins of the North and South Atlantic and Indian Oceans with near-bottom dissolved oxygen (DO) concentration from the NOAA Ocean Atlas (2005). Major basins defined by closed bathymetric contours (from the GSFM database; Harris et al. 2014), in which the *numbers* indicate depths of major ocean basins based on the most shallow, closed, bathymetric contour that defines the basin outline. *Arrows* indicate gradients of decreasing DO concentration within basins and between adjacent basins that are descending or approximately (± 100 m) equal in depth. The *arrows* and DO indicate southward flow of North Atlantic Deep Water ($NADW$) formed in the Norwegian and Labrador Seas and the northward flow of Antarctic Bottom Water ($AABW$) formed in the Weddell Sea and along the East Antarctic continental shelf. The depths illustrate how shallow basins adjacent to Antarctica at 4500 m feed into basins of the South Atlantic (at 4500 m) and finally into the deepest basins located in the northwest Pacific (at 5300 m)

sediments. It appears that seamounts are more common in the Pacific (declining basins) than in mature (Atlantic-type) ocean basins simply because Pacific seamounts are not buried in as much sediment and therefore have greater vertical expression than seamounts found in mature (more sediment-filled) ocean basins (Wright and Rothery 1998). In fact, among mature and declining ocean basins there is a trend for seamount concentration to decrease with increasing mean sediment thickness (Fig. 10).

To test the hypothesis that seamount abundance is a function of depth of sediment burial, we conducted an experiment using the available sediment thickness and seamount elevation data in the North and South Atlantic and the North and South Pacific Oceans. We note that the average sediment depth for the Atlantic is 1082 m (1442 m in North Atlantic and 772 m in South Atlantic), whereas the average sediment depth in the Pacific is 308 m (386 m in North Pacific and 229 in South Pacific). Thus the difference is on average 774 m. Recalling that the definition of seamounts used in this study specifies a minimum elevation of 1000 m above the level of surrounding seafloor and that the elevation of seamounts is

recorded in our database, we can adjust the number of apparent seamounts in different ocean areas by subtraction of elevation data. Subtracting 774 m from the elevations of seamounts in the South and North Pacific (both declining ocean basins) yields 2.0 and 3.1 seamounts per 100,000 km² for the South and North Pacific, respectively and subtracting 1000 m yields 1.6 and 2.7 seamounts per 100,000 km², respectively. The latter values (1.6 and 2.7 seamounts per 100,000 km²) are not significantly different from those of the North and South Atlantic (2.1 and 2.5 seamounts per 100,000 km², respectively).

4.3 Geomorphology and Global Bottom Water Circulation

Seafloor geomorphic features exert control over the flow of water within and between ocean basins. This occurs through bathymetric steering, the deflection of flow around obstacles and the constriction of flow through narrow choke points and over sills (Whitehead 1998; Gille et al. 2004). Here we focus on the flow of water between the 33 major bathymetric basins and pathways of flow that could be influenced (or in some cases actually determined) by their depth and configuration.

The formation of cold, dense water that occupies the abyssal layer of the global ocean occurs in the polar regions of the earth and it is driven by two major processes: (1) the cooling of Gulf Stream waters around Iceland to form North Atlantic Deep Water; and (2) the formation of bottom water by sea ice formation and brine rejection (Ivanov et al. 2004; Rintoul 2007). North Atlantic Deep Water (NADW) is formed as cold surface waters during the winter in the Greenland and Norwegian Seas. This water sinks to fill the basin north of a ridge spanning the distance from Greenland to Scotland (Whitehead 1998; Ivanov et al. 2004).

The coldest bottom water, Antarctic Bottom Water (AABW), is created in winter on the continental shelf of Antarctica by sea ice formation. It is about -1 °C and it fills basins in the Southern Ocean adjacent to Antarctica (Rintoul 2007). As dense AABW water flows into a bathymetric basin, the basin eventually becomes filled and overflows, driven by gravity. The descent of bottom water flowing from one basin into another (deeper) basin becomes focused at sills and bathymetric choke points. Sills are “a sea floor barrier of relatively shallow depth restricting water movement between basins” (IHO 2008). Thus every basin has a sill, over which fluid would escape if the basin were filled to overflowing. This leads to the consideration of bathymetric basins and their sills as factors controlling the flow of bottom water within and between ocean basins (see also Whitehead 1998).

Sills can be a biogeographic barrier for species located in deep basins on either side. The basin environments are vastly different from the shallow water depths, high current energy, and warmer water temperature of the sill environment. The Strait of Gibraltar is a type-case for geomorphic sills. Here, ocean circulation is characterized by a two-layer system: an eastward-directed, Atlantic water inflow at the surface and a deep westward outflow of saline Mediterranean water. The two different water layers have a variable interface depth of around 100 m and the Strait

of Gibraltar sill depth is located at a depth of around 200 m. De Mol et al. (2012) document reef-forming cold-water coral deposits up to 40 m in thickness in the deepest part of the Strait of Gibraltar between 180 and 330 m water depth, which have developed to exploit the unique oceanographic conditions. Coral buildups on the tops of north-south orientated rocky crests (i.e. oriented transverse to the direction of flow) are the most common form in the Strait of Gibraltar.

Another critical aspect of bottom water is that it is the source of oxygen for all benthic animals inhabiting the deep ocean environment, a property that could be affected by anthropogenic climate change (Long et al. 2016). As AABW and NADW sink into the deep ocean basins and move away from the poles they are gradually depleted of dissolved oxygen through the respiration of benthic fauna and oxidation of minerals and organic matter. Thus the concentration of dissolved oxygen in deep bottom waters is a conservative tracer that we can use to track pathways of bottom water dispersal in the abyssal ocean.

In order to examine the flow of water between bathymetric basins, we have plotted the near-bottom dissolved oxygen (DO) concentration from the NOAA Ocean Atlas (2005) and overlaid the major bathymetric basins defined by closed bathymetric contours from the GSFM database (Harris et al. 2014). The results (Figs. 11 and 12) illustrate how the bathymetric basins coincide remarkably well

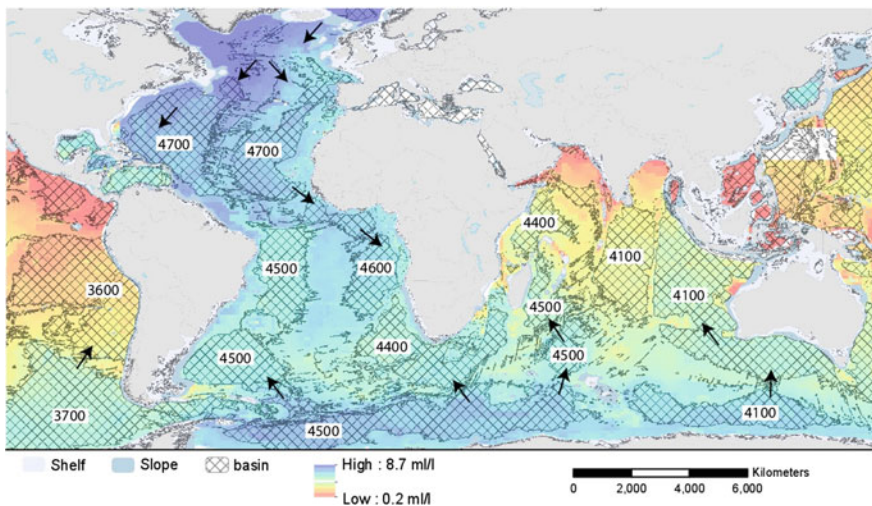


Fig. 11 Bathymetric basins of the Southern, Indian and North and South Atlantic Oceans with near-bottom dissolved oxygen (DO) concentration from the NOAA Ocean Atlas (2005). Major basins defined by closed bathymetric contours (from the GSFM database; Harris et al. 2014), in which the *numbers* indicate depths of major ocean basins based on the most shallow, closed, bathymetric contour that defines the basin outline. *Arrows* indicate gradients of decreasing DO concentration within basins and between adjacent basins that are descending or approximately (± 100 m) equal in depth. The *arrows* and DO indicate southward flow of North Atlantic Deep Water (NADW) formed in the North Atlantic and Arctic Oceans, and northward flow of Antarctic Bottom Water (AABW) formed in the Weddell Sea and along the East Antarctic continental shelf

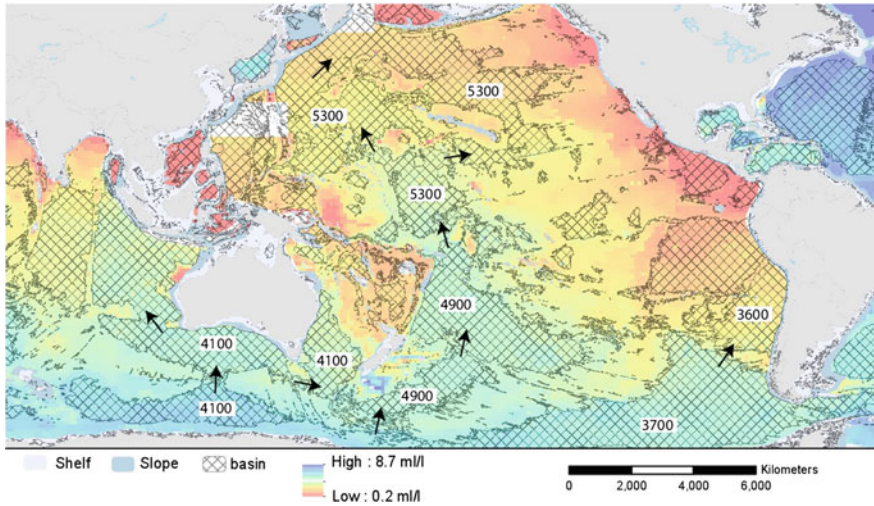


Fig. 12 Bathymetric basins of the Southern and North and South Pacific Oceans with near-bottom dissolved oxygen (DO) concentration from the NOAA Ocean Atlas (2005). Major basins defined by closed bathymetric contours (from the GSFM database; Harris et al. 2014), in which the numbers indicate depths of major ocean basins based on the most shallow, closed, bathymetric contour that defines the basin outline. Arrows indicate gradients of decreasing DO concentration within basins and between adjacent basins that are descending or approximately (± 100 m) equal in depth. The arrows and DO indicate northward flow of Antarctic Bottom Water (AABW) formed in the Ross Sea and along the East Antarctic continental shelf. The depths illustrate how shallow basins adjacent to Antarctica at 3700 and 4100 m feed into deeper basins of the central South Pacific (at 4900 m) and finally into the deepest basins located in the northwest Pacific (at 5300 m)

with discrete areas having like values of DO. Arrows shown on Figs. 11 and 12 indicate gradients of decreasing DO concentration within basins and between adjacent basins that are descending or approximately (± 100 m) equal in depth.

As NADW sinks into the North Atlantic it flows southwards into the (4900 m) deep basins located to the east and west of the mid-Atlantic ridge (Fig. 11). These bottom currents are consistent with the pattern inferred by Schmitz and McCartney (1993). The gradient in DO suggests a pattern of southward flow between basins located on the eastern side of the mid-Atlantic ridge as far south as the Gulf of Guinea (West Africa).

The dispersal of AABW water from the basin at 4500 m depth located adjacent to the Weddell Sea of Antarctica appears to flow into basins at a similar depth located adjacent to eastern South America (Argentine Basin) and also into the Indian Ocean basin adjacent to Madagascar (Fig. 11). This pattern is consistent with bottom flows suggested by Tchernia (1980). Bottom waters become depleted of DO with increasing distance northward into the Indian Ocean, reaching minima in the Bay of Bengal and in the Arabian Sea (Fig. 11).

The dispersal of AABW from the basin at 4100 m depth located adjacent to East Antarctica appears to flow into a basin at a similar depth adjacent to the southern

and western margins of Australia. Bottom waters become depleted of DO with increasing distance northward in this 4100 m basin, that extends northwards into the eastern Indian Ocean. The two basins at 4100 m depth located in the eastern Indian Ocean are divided by the 90 East Ridge, with the western basin being clearly more depleted of DO than the eastern basin (Fig. 11).

The dispersal of AABW water from the basin at 3700 m depth located adjacent to East Antarctica appears to involve the northward flow of water into a series of basins of increasing depth moving northwards from basins adjacent to New Zealand and into the western North Pacific Ocean (Fig. 12). This pattern is also consistent with bottom flows suggested by Tchernia (1980). As the water ages it becomes warmer and is depleted of oxygen along this pathway, reaching a minimum in the basins of the western North Pacific. At this point, at the end of the global ocean conveyor (Broecker 1991), it contains less than 1 ml/l dissolved oxygen.

5 Conclusions

The present study has shown how the evolution of the earth's ocean basins via the Wilson Cycle give rise to stages of geomorphological development that can be quantified using available digital datasets. Basins, formed initially by tectonic rifting of continental plates, evolve and are modified by volcanism and sedimentation processes. Young basins such as the Gulf of California and the Red Sea are characterized by the absence of ocean trenches, young ocean crust (<8 MA), comparatively large areas of continental slope, thick sediments, and a relatively large percent area of mid-ocean ridge rift valley (above 1.7%). Mature ocean basins are characterized by relatively large percentage areas of continental rise (mean of 19.8%) and submarine fans (mean of 4.3%), which is consistent with the relatively thick sediments deposited in these basins (mean thickness of 940 m). The area of ocean trench is relatively small in all mature ocean basins compared with declining and terminal basins, ranging from 0 to 0.3% (Table 2). A defining geomorphic feature of the declining category is that around 1% of their area is trench, which is more than twice the area of trenches contained in the other categories. Declining ocean basins contain the highest concentration of seamounts (3.5–5 seamounts per 100,000 km²), which is more than double the mean value (1.4 seamounts per 100,000 km²) that occurs for the mature category with the next highest concentration. The terminal category of ocean basins is represented only by the Mediterranean Sea. It is characterised by the greatest mean sediment thickness (4311 m) and greatest percentage area of submarine fans (7.2%) of any ocean basin.

Sedimentation is reduced in declining ocean basins by virtue of trenches and troughs that capture terrigenous sediments entering the basin, trapping them within the narrow subduction zone and inhibiting deposition seaward of the trench-trough system inside the basin. Consequently, sediment deposits within declining ocean basins are very thin, with mean thicknesses of 229 and 386 m in the South and North Pacific basins, respectively. The thin nature of sediment deposits in declining

ocean basins explains their greater apparent concentration of seamounts; seamounts are not buried in as much sediment in declining ocean basins and therefore have greater vertical expression than seamounts found in mature (more sediment-filled) ocean basins.

Areas having similar near-bottom dissolved oxygen (DO) concentrations derived from the NOAA Ocean Atlas (2005) coincide very well with major bathymetric basins defined by closed bathymetric contours from the GSFM database (Harris et al. 2014). Examination of gradients of decreasing DO concentration within basins and between adjacent basins suggests pathways of bottom water flow that are generally consistent with previously published assessments of bottom currents.

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