



# A global analysis of controls on submarine-canyon geomorphology

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## ABSTRACT

The role of possible controlling factors in influencing the geomorphology of submarine canyons has been investigated using a database of 282 globally distributed modern examples collated from the literature and open-source worldwide bathymetry. Canyon geomorphology has been characterised quantitatively in terms of maximum and average canyon dimensions, canyon sinuosity, average canyon thalweg gradient, and maximum canyon sidewall steepness. An assessment is made of how geomorphological characteristics vary with respect to the position of the canyon apex relative to the shelf break, continental-margin type, terrestrial source-to-sink system setting, oceanographic environment, and latitude. Scaling relationships between canyon morphometric parameters, and correlations between these and attributes of the canyon physiographic settings, terrestrial catchments, and continental shelves and slopes, have been quantified.

Key findings are as follows: (i) a number of scaling relationships describing canyon morphometry (e.g. scaling between maximum canyon dimensions, relationships of maximum canyon sidewall steepness with maximum canyon width and depth) can be recognised globally, suggesting their general predictive value; (ii) possible causal links are identified between hydrodynamic processes (e.g. upwelling, longshore- and along-slope currents) and canyon morphology; (iii) potential predictors of aspects of canyon geomorphology include whether a canyon is incised into the shelf or confined to the slope, the continental-margin type, the oceanographic environment, latitude, and shelf-break depth; (iv) similarity in the distributions of maximum width-to-maximum depth ratios across all settings suggests that the relative magnitudes of canyon-margin erosion and intra-canyon deposition do not vary greatly depending on setting or canyon size.

The relationships between canyon geomorphology and environmental variables identified in this study may be incorporated into conceptual models describing canyon geomorphology and its relationship both to other elements of deep-water systems, and to its broader source-to-sink context. The results provide a framework for future experimental and numerical studies of canyon geomorphology.

## 1. Introduction

Submarine canyons constitute important conduits for the transfer of water masses, sediment, nutrients, organic matter and pollutants between shallow- and deep-marine environments, across continental slopes (Harris and Whiteway, 2011; Fildani, 2017). They control the sorting and segregation of sediments that are ultimately deposited in deep-marine environments, via their morphology (e.g. Soutter et al., 2021; Wan et al., 2021) and distance from fluvial outlets and littoral cells (e.g. Sweet and Blum, 2016; Sweet et al., 2020). Their ability to intercept and influence oceanic currents along shelves (e.g. Jordi et al., 2008) and slopes (e.g. Marchès et al., 2007; Voigt et al., 2013), can set hydrodynamic conditions in vicinity of their location (e.g. Allen et al., 2001; Connolly and Hickey, 2014; Saldías and Allen, 2020). Submarine

canyons can impact the formation and evolution of slope systems by reducing local gradients (Orange et al., 1994), capturing and redirecting sediment pathways from adjacent canyons (e.g. Bernhardt et al., 2015), and functioning as tributaries to other canyons (e.g. Mountjoy et al., 2009). Buried canyons that are partially infilled can influence the pathways of younger ones by forming negative seafloor topography that can confine sediment transport (e.g. Pratson et al., 1994). Thus, they represent a crucial link for sediment routing from terrestrial hinterlands, across and along shelves and slopes, to intra-slope and basin-floor sinks.

The presence of submarine canyons can also influence the formation of gas hydrates (Crutchley et al., 2017) and the associated processes of trapping and release of hydrocarbons (e.g. Davies et al., 2012; Benjamin et al., 2015). Canyons can promote salt migration within the subsurface and impact the geometry of salt bodies (Fiduk, 1995), can increase the

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salinity of shelf waters via upwelling of deeper slope waters (e.g. Conolly and Hickey, 2014), and can tap into groundwater aquifers (e.g. Paldor et al., 2020). The association of submarine canyons with hydrocarbon-bearing deposits can promote vertical hydrocarbon migration and expulsion, which in turn can generate trains of pockmarks in younger canyons (e.g. Benjamin et al., 2015). Pockmarks can also form atop of canyon fills as a result of sediment compaction (e.g. Jobe et al., 2011); given that these structures can reach diameters of several hundred metres and depths of tens of metres (e.g. Jobe et al., 2011; Benjamin et al., 2015), their presence might affect canyon internal flows and flow pathways on the seafloor.

Submarine canyons are also important for faunal communities, for which they provide significant habitats. Aspects of their physiography have been suggested to exert control on the biodiversity and abundance of faunal assemblages; these aspects include canyon spacing, gradient, dendricity and sinuosity (Fanelli et al., 2018), canyon size and magnitude of incision of the shelf (Santora et al., 2018). The effect of submarine-canyon geomorphology on hydrodynamic processes also impacts the spatial distribution of faunal communities like zooplankton (Allen et al., 2001).

Submarine canyons are linked to potential geohazards, due to the ability of intra-canyon slope failures to trigger tsunamis (e.g. Orange et al., 1994; Power et al., 2016), and to the influence of canyon geomorphology on tsunami propagation (e.g. Aranguiz and Shibayama, 2013; Iglesias et al., 2014). Moreover, canyon-crossing seafloor telecommunication cables are at risk of breakage from canyon-margin failure and canyon-traversing sediment gravity flows (e.g. Heezen and Ewing, 1952; Hsu et al., 2008; Carter et al., 2014). Such flows are also considered responsible for the displacement of marine pipelines (e.g. Porcile et al., 2020), hence posing a hydrocarbon leakage hazard, for example. Moreover, it has been suggested that the upslope transport of warm water currents through submarine canyons along Antarctica contributes to the acceleration of ice sheet loss, which in turn influences global sea-level rise (e.g. Morrison et al., 2020; Gales et al., 2021, and references therein).

The sedimentary fills of submarine canyons, and their linkage to down-system submarine fans (e.g. Covault et al., 2011b; Jobe et al., 2011) and contourite-drift systems (e.g. Wang et al., 2018; Warratz et al., 2019; Serra et al., 2020; Rodrigues et al., 2022, and references therein), make them important references and targets for hydrocarbon exploration. Canyons can represent significant sinks for both macro- (e.g. Pierdomenico et al., 2019; Zhong and Peng, 2021) and micro-pollutants (e.g. Azaroff et al., 2020).

Hence, the study of submarine canyons represents a key area of interest for research linked to a broad range of scientific disciplines (Matos et al., 2018).

Source-to-sink (S2S) research investigates sediment budget dynamics and process-response relationships in both ancient and modern sedimentary systems. Scaling relationships between sedimentary systems and attributes of segments of the S2S profile are commonly established. However, the focus of such studies has been chiefly on fluvial systems and submarine fans, whereas the submarine canyons that link them remain relatively understudied (e.g. Sømme et al., 2009; Nyberg et al., 2018).

Quantitative studies provide a means for the systematic investigation of scaling relationships across and within sedimentary environments, with consideration of environmental controls such as climate, hydrodynamic processes, or tectonic setting, which dictate sediment source areas, transport pathways and sinks (e.g. Wang et al., 2019, 2020; Budai et al., 2021; Cosgrove et al., 2021). Such studies enable an assessment of the relative importance of autogenic versus allogenic controls on aspects of the geomorphology, architecture and facies characteristics of sub-environments, and of scaling-relationships they may exhibit. Such insights can be applied to infer the geometrical characteristics of formative subenvironments based on preserved architectures seen in outcrop and subsurface studies (e.g. Martinsen et al., 2010; Xu et al., 2017), and to

inform laboratory and modelling studies (Nyberg et al., 2018). The applied usefulness of scaling relationships for the reconstruction and modelling of sedimentary systems at different scales of observations has been highlighted by various authors (e.g. Sømme et al., 2009; Martinsen et al., 2010; Helland-Hansen et al., 2016; Bhattacharya et al., 2016; Xu et al., 2017; Nyberg et al., 2018).

Scaling relationships between aspects of canyon geomorphology and controlling factors have been identified in quantitative studies of submarine canyons at regional, continental, and global scales (see section 2.2). However, relationships between canyon morphometric parameters have only been partially investigated using global datasets, and the general applicability of such relationships across environmental settings is largely unconstrained. This study addresses these knowledge gaps.

The aim of this study is to improve our understanding of controlling factors on submarine-canyon geomorphology, and of the extent to which scaling relationships of canyon morphometric parameters – both mutually and with attributes of their physiographic and environmental setting – can be recognised in modern canyons. To achieve this, a global database has been built utilising datasets from published case studies of submarine canyons combined with data obtained from open-source bathymetry to support the following research objectives:

- (i) to characterize morphometric parameters of submarine canyons, both generally and with consideration of the role of environmental factors (canyon-apex location relative to the shelf-break, continental-margin type, source-to-sink system setting, oceanographic environment and climate zones);
- (ii) to identify and assess scaling relationships between canyon morphometric parameters;
- (iii) to evaluate relationships between canyon morphometric parameters and other variables, including canyon bathymetry, distance between the canyon apex and the shoreline, attributes of the catchment, shelf and slope, and latitude of the canyon;
- (iv) to identify and discuss possible causal links between observed scaling relationships and autogenic and allogenic controls, the configuration of the associated source-to-sink system, and the environmental setting.

## 2. Background

### 2.1. Controls on submarine canyon evolution

Submarine canyons are highly complex sedimentary systems whose evolution is influenced by a wide range of processes and environmental factors (e.g. Shepard, 1936, 1981; Pratson and Coakley, 1996; Pratson et al., 2007), as demonstrated in the recent comprehensive literature reviews by Puig et al. (2014) and Amblas et al. (2017). Despite being well studied, the genesis and long-term evolution of submarine canyons remain topics of ongoing debate, and require further understanding (e.g. Pratson et al., 2007, and references therein; Baztan et al., 2005; Puig et al., 2014; Smith et al., 2017, 2018). The relative importance of controls on canyon geomorphology is still not well understood (Li et al., 2022).

Various physiographic and environmental factors are known to influence canyon evolution by exerting controls on connectivity to sediment sources, on mechanisms of sediment distribution, and on types of canyon evolutionary processes. Physiographic factors that have been invoked include the distance of the canyon to fluvial outlets and littoral cells (e.g. Sweet and Blum, 2016; Sweet et al., 2020), shelf width and gradient in the vicinity of the canyon (e.g. Covault and Graham, 2010; Gamberi et al., 2015; Jipa and Panin, 2020; Bernhardt and Schwanghart, 2021), and continental-slope gradients (e.g. McGregor, 1983; Orange et al., 1994; Lo Iacono et al., 2014). Environmental factors comprise local- and regional-scale tectonics (e.g. Ratzov et al., 2012; Micallef et al., 2014; de Almeida et al., 2015; Soutter et al., 2021), sea-level fluctuations (e.g. Rasmussen, 1994; Mitchell et al., 2007; Maier et al.,

2018), and climate (e.g. Henrich et al., 2010), including glaciations (e.g. Harris et al., 2014; Gales et al., 2021).

The oceanographic regime is also thought to influence gully formation and failures along canyon walls (e.g. Wang et al., 2022), and is a possible cause for particular geomorphic characteristics of Arctic and Antarctic gullies (Gales et al., 2013). Also, a global study of late Quaternary incised-valley fills by Wang et al. (2020) demonstrated that the facies architecture of valley fills varies across open oceans and semi-enclosed and enclosed seas, which exhibit contrasting hydrodynamics. Considering the role of marine hydrodynamic processes in the delivery of sediment to canyons, and in intra-canyon sediment transport and erosion (see section 4.2.2), and given the genetic linkage between cross-shelf lowstand fluvial systems and submarine canyons (e.g. Harris and Whiteway, 2011; Maier et al., 2018), more research is needed to establish whether and how canyon geomorphology varies as a function of the oceanographic setting.

Anthropogenic influences can also affect the evolution of modern submarine canyons, in several ways. Sediment gravity flows can be triggered by trawling (e.g. Palanques et al., 2006; Lopez-Fernandez et al., 2013), whereas farming and deforestation (e.g. Milliman and Farnsworth, 2011), and the artificial diversion (e.g. Higgins et al., 2018) or damming of rivers (e.g. Sheng et al., 2019) may impact catchment processes and fluvial discharge rates, which in turn can impact sediment delivery to submarine canyons (e.g. Mazières et al., 2014; Puig et al., 2017).

## 2.2. Submarine canyon studies

Submarine canyons have been the subject of many prior studies: Matos et al. (2018) conducted a review of the scientific literature on submarine canyons published between 1929 and 2016, considering 1,968 publications. These authors identified a geographical bias in prior canyon research: less than 10% of the canyons mapped globally by Harris et al. (2014) are covered by the literature, and almost half of the 1,968 publications concentrate exclusively on 11 intensively studied submarine canyons. Consequently, research efforts have largely been directed towards the particular environmental conditions and set of controls associated with a limited subset of canyons, depending on the thematic focus of the case study (see Matos et al., 2018). However, the rate at which studies on submarine canyons are published has further accelerated in recent years (Matos et al., 2018), due in part to technological advances in data acquisition and processing (e.g. Xu, 2011; Urías Espinosa et al., 2016; Simmons et al., 2020; Bailey et al., 2021). Here we summarise examples of regional, continental, and global-scale quantitative studies of submarine-canyon geomorphology that consider the canyon physiographic and environmental setting, focussing on aspects of these studies that are relevant to the research presented in this paper.

Canyon classification schemes based on case studies from specific regions have been proposed to be universally applicable, for example where specific sets of controls are associated with a canyon (canyon-head location relative to the shelf break, type of intracanyon sedimentary processes, sediment sources and sediment characteristics; cf. Jobe et al., 2011), and models for canyon evolution have been considered relevant to canyons that developed under similar external controls, as for canyons associated with active margins (e.g. Micallef et al., 2014). However, a study of 713 submarine canyons located offshore Australia by Huang et al. (2014) revealed great variability and complexity in aspects of canyon geomorphology at the continental scale, which challenges the applicability of insights generated by regional studies at a larger scale. The authors established a hierarchical classification of shelf-incising and slope-confined canyons based on the following canyon metrics: percentage of canyon area characterised by slope gradients exceeding 15°, average canyon thalweg gradient, volume subtended by the canyon channelform, canyon-head incision depth, and distance to the nearest neighbouring canyon. Their findings demonstrate a higher number of canyon classes for slope-confined canyons compared to shelf-

incising ones (see Figures 6 & 7 of Huang et al., 2014).

Relationships between canyon geomorphology and the position of the canyon head relative to the shelf-break were also recognised in other regional-scale studies. In a study of 80 canyons offshore California (Santora et al., 2018), differences in frequency distributions of canyon dimensions were documented across shelf-incising versus slope-confined canyons, whereby shelf-incising canyons tend to have greater areas, lengths, widths and mean depths. Additionally, the authors found that canyon area scaled positively with canyon length and width, independently of the canyon-head location relative to the shelf-margin. Li et al. (2022) documented pronounced differences in 48 shelf-incised submarine canyons from the northwest South China Sea.

Furthermore, relationships between characteristics of S2S systems and canyon geomorphology are demonstrated in a number of regional-scale studies. For example, Jipa and Panin (2020) noted that the few submarine canyons in the N and NW region of the Black Sea were associated with continental shelves up to 200 km wide, large fluvial systems of several thousand kilometres length and low-relief catchments of up to several hundred metres elevation. Such canyons were characterised by a single main stem and had large submarine fans as distal segments. By contrast, submarine canyons along the E and NE Black Sea margins, characterised by (i) high-elevation catchments, (ii) short feeder rivers (up to several hundred kilometres length), and (iii) shelves that are rarely wider than 15 km, tend to form dendritic drainage networks and are more closely spaced; also, their submarine fans tend to form a continuous apron-like zone. Their findings were in part corroborated by those of Fernane et al. (2022), who demonstrated that submarine canyons along the western Algerian margin display a greater degree of dendricity and incision into the shelf where they are associated with a narrow shelf configuration compared to canyons associated with wide shelf margins.

For the interpretation of autogenic and allogenic controls on canyon geomorphology, an improved understanding of the sensitivity of canyon morphometric parameters to seafloor processes and environmental factors is required. In contrast to regional studies, global-scale studies have the potential to constrain the variability in potential controls more fully in a broad range of environmental settings. Previous global-scale studies that have investigated aspects of submarine canyon geomorphology (e.g. Nelson et al., 1970; De Pippo et al., 1999; Sømme et al., 2009; Covault et al., 2011a; Harris and Whiteway, 2011; Harris et al., 2014; Soutter et al., 2021) and assessed the relative importance of factors promoting sediment-connection of canyons to shorelines (Bernhardt and Schwanghart, 2021) constitute important contributions to a fuller understanding of submarine canyon evolution. Nevertheless, such global investigations of the geomorphology of modern submarine canyons have been limited to individual canyon morphometric parameters and to consideration of specific environmental controls, with the datasets being limited in terms of their geographic coverage prior to the advent of a global inventory of modern submarine canyons – comprising 5,849 canyons – compiled by Harris and Whiteway (2011).

In their global study, De Pippo et al. (1999) compiled a database of selected aspects of the geomorphology of 50 submarine canyons, including canyon length, average gradient, and cross-sectional profile, together with variables describing their environmental setting (see Figure 1 of De Pippo et al., 1999). For example, the authors applied their database to tease out possible relationships between canyon geomorphology and potential controls posed by the morphological and tectonic characteristics of the associated continental margin; they additionally assessed relationships between canyon morphometric parameters, e.g. for canyon length and average canyon thalweg gradient (see Figure 5 of De Pippo et al., 1999).

Leveraging advancements in bathymetric mapping of seafloors, the study by Harris and Whiteway (2011) provided a summary of aspects of canyon geomorphology and their physiographic setting for 5,849 submarine canyons classified on geographic region, continental-margin type, location of the canyon-head relative to the shelf-break and

connection to a fluvial system. The following variables were considered: canyon length, average thalweg gradient, average sinuosity, bathymetric range, spacing, and dendricity; descriptive statistics were presented for canyons classified on margin type, canyon-head location relative to the shelf break, connection to a fluvial system, and geographic region (Table 1 of Harris and Whiteway, 2011). Statistical analyses revealed that active-margin canyons are on average steeper and shorter than their counterparts along passive margins, whereas overall canyon sinuosity tends to be similar (Figure 8 of Harris and Whiteway, 2011). In addition, the authors documented relationships between mean values of canyon parameters obtained for groups of canyons classified by geographic regions and distinguished into active- and passive-margin settings. Canyons associated with an insular-margin setting were excluded from the correlation analyses. Moreover, the authors demonstrated the lack of a relationship between latitude and average canyon sinuosity for shelf-incising canyons (Figure 9 of Harris and Whiteway, 2011). The importance of fluvial sediment connection on canyon length was inferred from the observation that canyons associated with fluvial systems and incising the shelf tend to be longer than shelf-incising canyons without a river connection and slope-confined canyons, by factors 1.60 and 2.07, respectively. In non-polar regions, Harris and Whiteway (2011) showed a positive linear relationship between the percentage of shelf-incising canyons in a geographic region and sediment discharge from rivers (Figure 10 of Harris and Whiteway, 2011).

In the first published digital geomorphic seafloor map by Harris et al. (2014), the authors identified 9,477 submarine canyons. The significant number of newly recognised canyons reflect in part the higher resolution of seafloor data, but also the fact that canyons associated with plateaux adjoined to continental margins were also incorporated, unlike in Harris and Whiteway (2011; see Harris et al., 2014). Harris et al. (2014) calculated mean values of canyon area and length both for the global dataset and separately for major geographic regions. The results were further distinguished based on the location of the canyon head relative to the shelf break. In addition, the mean incision depth was reported for shelf-incising canyons in all regions (see their Table 9) and for slope-confined ones in general (Harris et al., 2014). On average, canyons in the latter group display greater average depth, shorter lengths and about half the area, compared to canyons that incise the shelf. Harris et al. (2014) also showed that submarine canyons in polar regions are, on average, about twice as large in area relative to the global average; in addition to characteristics of the slope and basin-floor environments in these settings, Harris et al. (2014) linked these attributes to a control by sediment supply to deep-marine environments during glacial intervals of the Cenozoic. Arctic and Antarctic canyons tend to be the longest of all differentiated geographic regions, but only by a modest margin; compared to submarine canyons in the South Atlantic, for example, their average lengths are only 1.20 and 1.21 times larger. Shelf-incising canyons of the Arctic and Antarctica also tend to have the largest values of mean incision depth across all investigated regions, but on average they are only 1.035 and 1.006 times deeper than canyons in the North Atlantic. These findings, together with the low variability in mean values of average canyon sinuosity for polar and non-polar regions documented by Harris and Whiteway (2011), suggest that factors related to latitudinal setting variably control aspects of submarine-canyon geomorphology, and that the strength in scaling might show pronounced regional variabilities.

Two global studies that have focused on the longitudinal profiles of submarine canyons are the studies by Covault et al. (2011a) and Soutter et al. (2021), who investigated the longitudinal profiles of a combination of 20 canyon and channels and of 377 submarine canyons, respectively. Covault et al. (2011a) established links between the longitudinal-profile shape – classified as convex, slightly concave or very concave – and both the margin type and the depositional architecture of deep-water environments (see their Fig. 9). Soutter et al. (2021) instead investigated and discussed relationships between the Normalised Concavity Index of canyon profiles and controlling factors including attributes of the

terrestrial catchment, climate and tectonic setting, as well as canyon-head location relative to the shelf break. The authors inferred a dominant tectonic control on canyon concavity, that the connection to a river is a secondary control, and that the climate of the hinterland is a relatively subordinate factor.

Collectively, these examples document the variability in canyon morphometrics but in a way that suggests that there is no individual factor or single set of overriding controls emerging from their analyses.

The quantitative global assessment of canyon geomorphology undertaken in this study with consideration of aspects of the S2S system and of the environmental and physiographic setting aims to augment the findings of these earlier studies, and the current empirical knowledge of canyon geomorphology and of its links to potential controls.

### 3. Dataset and methodology

A database was collated that stores data describing the geomorphology of submarine canyons, their environmental context and geological controlling factors. Data have been sourced from 282 globally distributed modern submarine canyons and have been grouped into 96 separate case studies, with each case study corresponding to the study of one or several submarine canyons by a particular group of researchers (Fig. 1. and Table 1). The database comprises literature-derived, high-resolution bathymetric surveys of the seabed and high-resolution seismic datasets of the shallow subsurface, derived from 135 publications (Table 1) and open-source worldwide bathymetry data sets (<https://www.ncei.noaa.gov/maps/bathymetry/>, n.d, GEBCO 2019 NOAA NCEI Visualization; Google Earth).

#### 3.1. Submarine canyon definition

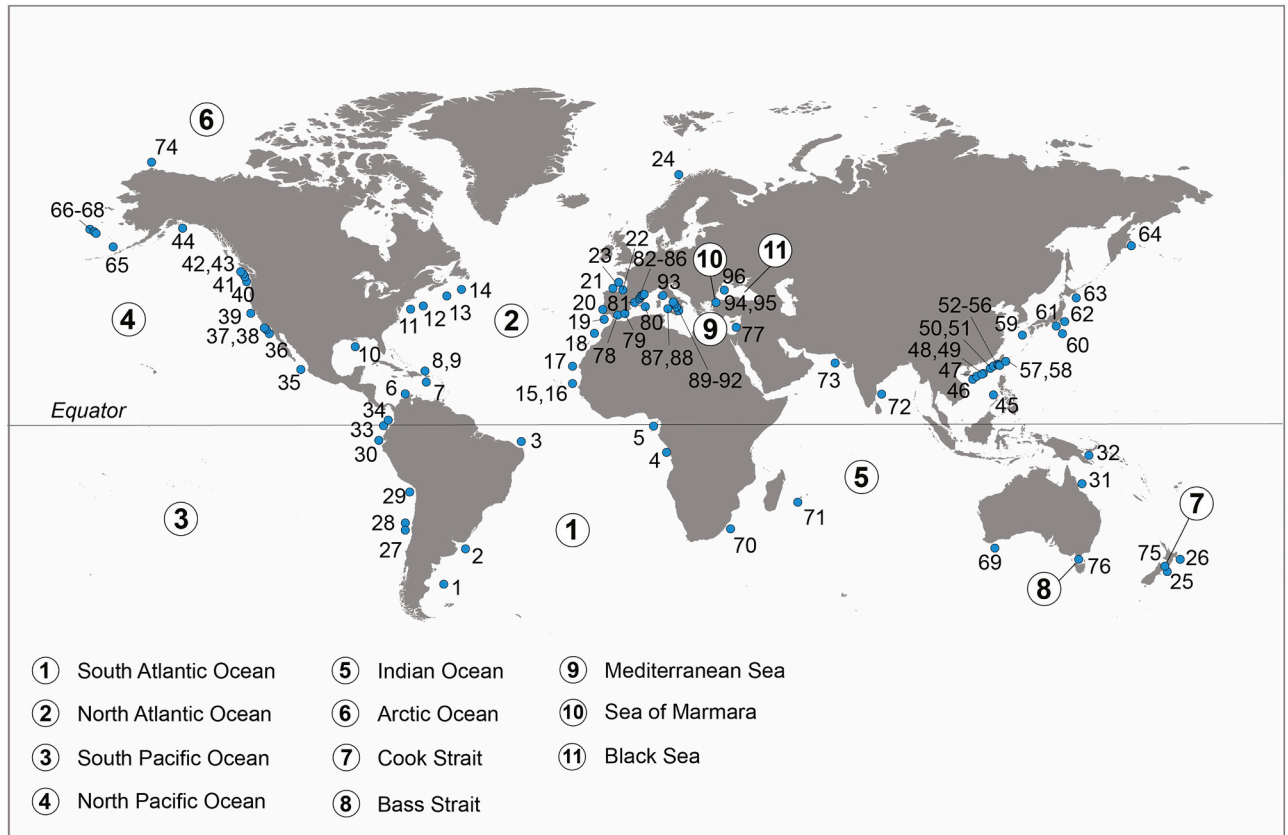
In this study, a submarine canyon is defined as a single dominantly erosional channel form incised into a continental slope. The chosen definition of submarine canyon does not consider criteria relating to bathymetric setting, minimum canyon dimensions (cf. Harris and Whiteway, 2011), genetic origin, or canyon cross-sectional shape, and is therefore inclusive of what other authors commonly refer to as ‘gullies’ (e.g. Field et al., 1999; Gales et al., 2013; Chen et al., 2017), ‘gulleys’ (e.g. Gulliksen, 1978) or ‘potential submarine canyons’ (e.g. de Almeida et al., 2015). A general definition was adopted for the following reasons: (i) submarine gullies have been considered to constitute forms at the early stage of canyon formation (e.g. Amblas et al., 2017); (ii) canyon geomorphologic attributes such as canyon size can be inherently limited by their physiographic setting; and (iii) both terms are variably used for smaller-scale erosional channel-forms on the slope.

The canyon apex is defined as the point of the shallowest bathymetry and canyon mouth as the most distal point, along a canyon axis. The term “canyon apex” has been used herein in preference to “canyon head”, the latter being a common but loosely defined term in the literature referring to the proximal part of a submarine canyon. Therefore “canyon apex” is used *sensu stricto* and “canyon head” *sensu lato*. In networks of connected channel forms, each channel-form is treated as an individual submarine canyon, whereas the network itself is termed a ‘canyon system’ (e.g. Mitchell et al., 2007; Mountjoy et al., 2009).

#### 3.2. Study variables

Data on submarine canyons, environmental setting and external controlling factors have been coded in the form of attributes recorded in the Deep-Marine Architecture Knowledge Store (DMAKS; Cullis et al., 2019). DMAKS is a relational database that allows the systematic and standardised collation of data on deep-water sedimentary systems, as originally obtained using different methods (e.g. outcrop, core, seismic, bathymetric, sonar imaging). DMAKS stores data on the architectural, geomorphological and facies characteristics of deep-water depositional systems, as well as on their external controls and depositional context

A.



B.

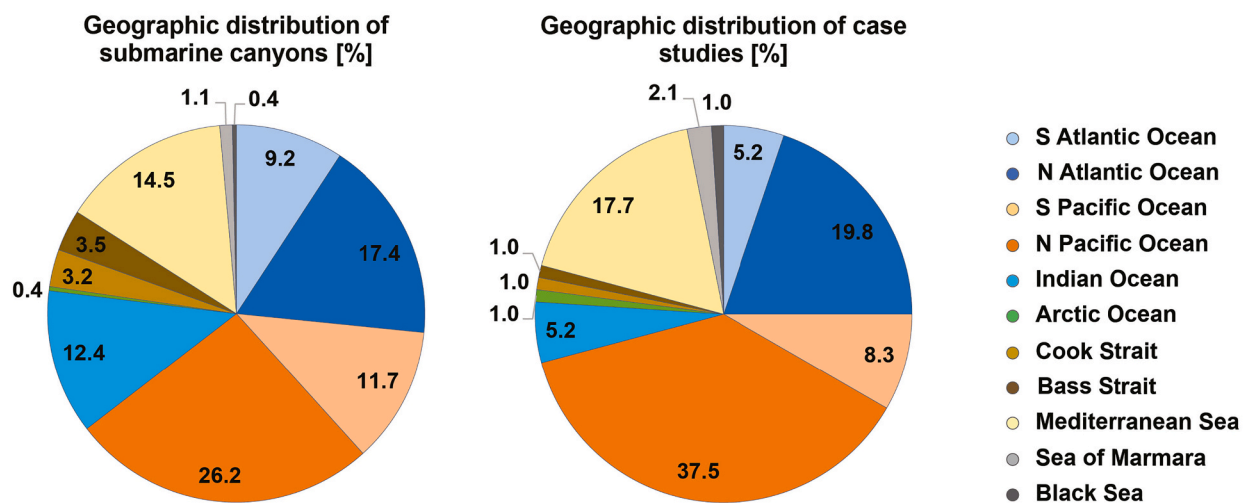


Fig. 1. A. Overview map of distribution of the 96 case studies. B. Geographic distribution of the 96 case studies and 282 studied submarine canyons (World map from [freevectormaps.com](https://www.freevectormaps.com)).

(Cullis et al., 2019). Several additional bespoke attributes have been added to DMAKS to enable the present study.

The dataset for this study has been obtained from multiple sources, including the peer-reviewed literature and government agency sources. Values were extracted from the texts or manually measured or calculated by us. Inherent to this approach are various sources of error, including the heterogeneity of the dataset and undetected errors in the primary datasets; these limitations are discussed in section 3.3.

The full set of variables employed in the analyses undertaken in this

study is summarised in Table 2.

### 3.2.1. Canyon morphometric parameters

Canyon geomorphology has been characterised by the following six morphometric parameters: (i) canyon length, (ii) canyon width (maximum and streamwise average), (iii) canyon bankfull depth (maximum and streamwise average), (iv) overall canyon sinuosity, (v) average canyon thalweg gradient, and (vi) maximum canyon sidewall steepness (Fig. 2a). Definitions of these variables are reported in Table 2.

**Table 1**

Overview of the 96 case studies and associated 135 literature data sources of the present study. Numbers in brackets refer to channel forms termed as submarine 'gullies' by the authors. See Fig. 1 for locations.

ID	Case study	No. of canyons	Oceanic region	Reference(s)
1	Patagonia canyons, SE Argentina	8	South Atlantic Ocean	Lastras et al., 2011a
2	Mar del Plata Canyon, E Argentina	1	South Atlantic Ocean	Krastel et al., 2011; Warratz et al., 2019
3	Potiguar Basin canyons, NE Brazil	14	South Atlantic Ocean	de Almeida et al., 2015
4	Congo Canyon, W Democratic Republic of Congo	1	South Atlantic Ocean	Babonneau et al., 2002; Ferry et al., 2004
5	Avon and Mahin canyons, SW Nigeria	2	South Atlantic Ocean	Jimoh et al., 2018
6	Aguja Canyon, N Colombia	1	North Atlantic Ocean (Caribbean Sea)	Restrepo-Correa and Ojeda, 2010
7	Guayanilla canyon system, S Puerto Rico	4	North Atlantic Ocean (Caribbean Sea)	Trumbull and Garrison, 1973
8	Arecibo and Quebradillas canyons, NW Puerto Rico	2	North Atlantic Ocean	Gardner et al., 1980
9	Mona Canyon, NW Puerto Rico	1	North Atlantic Ocean	Mondziel et al., 2010
10	Mississippi Canyon, S USA	1	North Atlantic Ocean (Gulf of Mexico)	Coleman et al., 1982
11	Hudson Canyon, NE USA	1	North Atlantic Ocean	Rona et al., 2015
12	Lydonia and Oceanographer canyons, NE USA	2	North Atlantic Ocean	Valentine et al., 1980
13	Logan Canyon, SE Canada	1	North Atlantic Ocean	Li et al., 2019
14	SW Grand Banks Slope canyons, SE Canada	3	North Atlantic Ocean	Armitage et al., 2010
15	Dakar Canyon, W Senegal	1	North Atlantic Ocean	Pierau et al., 2010, 2011
16	Cayar Canyon, W Senegal	1	North Atlantic Ocean	Dietz et al., 1968
17	Timiris Canyon, NW Mauritania	1	North Atlantic Ocean	Krastel et al., 2004; Antobreh and Krastel, 2006
18	Agadir Canyon, SW Morocco	1	North Atlantic Ocean	Ercilla et al., 1998; Wynn et al., 2002
19	Faro and Portimao canyons, SW Portugal	2	North Atlantic Ocean (Gulf of Cadiz)	Mulder et al., 2006
20	Nazaré, Cascais and Setubal-Lisbon canyons, W Portugal	4	North Atlantic Ocean	Arzola et al., 2008; Lastras et al., 2009; Allin et al., 2016
21	Aviles Canyon system and Navia canyon, N Spain	5	North Atlantic Ocean (Bay of Biscay)	Gómez-Ballesteros et al., 2014
22	Capbreton Canyon, SW France	1	North Atlantic Ocean (Bay of Biscay)	Mazières et al., 2014
23	Audierne and Blackmud canyons, SW France	2	North Atlantic Ocean (Bay of Biscay)	Mulder et al., 2012a, 2012b
24	Lofoten-Vesterålen canyons (incl. Andøya Canyon), NW Norway	15	North Atlantic Ocean	Rise et al., 2013
25	Kaikoura Canyon, E New Zealand	1	South Pacific Ocean	Lewis and Barnes, 1999
26	Lachlan Canyon, NE New Zealand	1	South Pacific Ocean	Walsh et al., 2007

**Table 1 (continued)**

ID	Case study	No. of canyons	Oceanic region	Reference(s)
27	Biobío Canyon system, SW Chile	2	South Pacific Ocean	Bernhardt et al., 2015
28	San Antonio Canyon, NW Chile	1	South Pacific Ocean	Hagen et al., 1996; Laursen and Normark, 2002
29	E Arequipa Basin canyons, NW Chile	3	South Pacific Ocean	Hagen et al., 1994
30	Guayaquil and Santa Elena canyons, NW Ecuador	2	South Pacific Ocean	Michaud et al., 2015
31	N Great Barrier Reef canyons, NE Australia	15	South Pacific Ocean (Coral Sea)	Puga-Bernabéu et al., 2011
32	Solomon Sea canyons, E and SE Papua New Guinea	8	South Pacific Ocean (Solomon Sea)	Davies et al., 1987; Galewsky and Silver, 1997
33	Esmeraldas Canyon, NW Ecuador	1	North Pacific Ocean	Michaud et al., 2015
34	Mira and Patia canyons, SW Colombia	2	North Pacific Ocean	Ratzov et al., 2012
35	Ipala Canyon, W Mexico	1	North Pacific Ocean	Urfías Espinosa et al., 2016
36	La Jolla and Scripps canyons, SW USA	2	North Pacific Ocean	Le Dantec et al., 2010; Paull et al., 2013
37	Redondo, Santa Monica and Dume canyons, SW USA	3	North Pacific Ocean	Gardner et al., 2003; Tubau et al., 2015
38	Mugu and Hueneme canyons, SW USA	2	North Pacific Ocean	Piper et al., 1999;
39	Monterey and Soquel canyons, SW USA	2	North Pacific Ocean	Greene et al., 2002; Xu and Noble, 2009
40	Astoria Canyon, NW USA	1	North Pacific Ocean	Hickey, 1997; Bosley et al., 2004
41	Quinault Canyon, NW USA	1	North Pacific Ocean	Baker and Hickey, 1986; Carson et al., 1986
42	Juan de Fuca Canyon, NW USA	1	North Pacific Ocean (heads in the Juan de Fuca Strait)	Alford and MacCready, 2014
43	Barkley Canyon, SW Canada	1	North Pacific Ocean	Allen et al., 2001
44	Tarr Canyon, NW USA	1	North Pacific Ocean (Gulf of Alaska)	Carlson et al., 1990
45	North Palawan Canyon, S China	1	North Pacific Ocean (South China Sea)	Yin et al., 2018
46	Modern Central Canyon, S China	1	North Pacific Ocean (South China Sea)	Su et al., 2015
47	3 canyons and 4 gullies, S China	3 (4)	North Pacific Ocean (South China Sea)	Chen et al., 2017
48	Pearl River Mouth Basin canyons, S China	17	North Pacific Ocean (South China Sea)	Han et al., 2010; Su et al., 2020
49	Zhujiang/Pearl River Canyon, S China	1	North Pacific Ocean (South China Sea)	Han et al., 2010; Ding et al., 2013
50	Dongsha Canyon, S China	1	North Pacific Ocean (South China Sea)	Yin et al., 2015
51	Taiwan Canyon, SW Taiwan	1	North Pacific Ocean (South China Sea)	Xu et al., 2014
52	Hongsai Canyon, SW Taiwan	1	North Pacific Ocean (South China Sea)	Yu and Chiang, 1995

(continued on next page)

Table 1 (continued)

ID	Case study	No. of canyons	Oceanic region	Reference(s)
53	Fangliao Canyon, SW Taiwan	1	North Pacific Ocean (South China Sea)	Yu and Lu, 1995; Chiang et al., 2012
54	Gaoping/Kaoping Canyon, SW Taiwan	1	North Pacific Ocean (South China Sea)	Chiang and Yu, 2006; Liu et al., 2016
55	Kaohsiung Canyon, SW Taiwan	1	North Pacific Ocean (South China Sea)	Yu et al., 1992
56	Penghu Canyon, SW Taiwan	1	North Pacific Ocean (South China Sea)	Yu and Chang, 2002; Hsiung and Yu, 2011; Su et al., 2015
57	Taitung Canyon, SE Taiwan	1	North Pacific Ocean (Philippine Sea)	Schnürle et al., 1998
58	Hualien Canyon, SE Taiwan	1	North Pacific Ocean (Philippine Sea)	Hsiung et al., 2017
59	Goto Canyon, SW Japan	1	North Pacific Ocean (East China Sea)	Oiwane et al., 2011
60	Aoga Shima Canyon, SE Japan	1	North Pacific Ocean (Philippine Sea)	Klaus and Taylor, 1991
61	Tenryu Canyon, SE Japan	1	North Pacific Ocean	Soh and Tokuyama, 2002
62	Boso Canyon, SE Japan	1	North Pacific Ocean	Soh et al., 1990
63	Kushiro Canyon, NE Japan	1	North Pacific Ocean	Noda et al., 2008; Noda and TuZino, 2010; TuZino and Noda, 2010
64	Submarine canyons of Kamchatka, NE Russia	7	North Pacific Ocean	Gnibidenko and Svarichevskaya, 1984
65	Bering Canyon, Bering Sea	1	North Pacific Ocean (Bering Sea)	Carlson and Karl, 1988; Harris and Whiteway, 2011
66	Zhemchug, Pervenets and Navarin canyons, Bering Sea	3	North Pacific Ocean (Bering Sea)	Carlson and Karl, 1988
67	Middle canyon system, Bering Sea	2	North Pacific Ocean (Bering Sea)	Carlson and Karl, 1984, 1988
68	St. Matthew canyon system, Bering Sea	2	North Pacific Ocean (Bering Sea)	Carlson and Karl, 1984, 1988
69	Albany canyons, SW Australia	11	Indian Ocean	Exon et al., 2005
70	Tugela Canyon, E South Africa	1	Indian Ocean	Wiles et al., 2013
71	Saint-Etienne and Pierrefonds canyons, SW La Reunion	2	Indian Ocean	Babonneau et al., 2013
72	Palar Basin canyons, E India	20	Indian Ocean	Susanth et al., 2021
73	Indus Canyon, SE Pakistan	1	Indian Ocean (Arabian Sea)	von Rad and Tahir, 1997; Salmanidou et al., 2019
74	Barrow Canyon, NW USA	1	Arctic Ocean	Eittrheim et al., 1982; Pisareva et al., 2019
75	Cook Strait canyons, E New Zealand	9	Cook Strait	Mountjoy et al., 2009, 2014; Micallef et al., 2014
76	Bass canyon system, SE Australia	10	Bass Strait	Mitchell et al., 2007
77	Akhviz and Sour canyons, NW Israel	2	Mediterranean Sea	Mart, 1989; Almagor, 1993
78	Almeria, Western, Eastern and	4	Mediterranean Sea	Alonso and Ercilla, 2003; Palanques et al., 2005

Table 1 (continued)

ID	Case study	No. of canyons	Oceanic region	Reference(s)
	Guadiaro canyons, S Spain			
79	Alfias-Almanzora canyon system, SE Spain	4	Mediterranean Sea	Puig et al., 2017
80	Menorca Canyon, SW Menorca, Balearic Islands	1	Mediterranean Sea	Acosta et al., 2002
81	Orpesa Canyon, NE Spain	1	Mediterranean Sea	Amblas et al., 2012
82	Foix Canyon system, NE Spain	3	Mediterranean Sea	Puig et al., 2000; Tubau et al., 2013
83	Blanes Canyon, SE France	1	Mediterranean Sea	Lastras et al., 2011b
84	Palamós/La Fonera Canyon, NE Spain	1	Mediterranean Sea	Martín et al., 2006; Palanques et al., 2006; Lastras et al., 2011b
85	Cap de Creus Canyon, NE Spain	1	Mediterranean Sea	Baztan et al., 2005; Lastras et al., 2007, 2011b
86	Bourcart Canyon, SE France	1	Mediterranean Sea	Mauffrey et al., 2015
87	Gulf of Palermo canyons, NW Sicily, Italy	7	Mediterranean Sea	Lo Iacono et al., 2011, 2014
88	Gulf of Castellammare canyons, NW Sicily, Italy	2	Mediterranean Sea	Lo Iacono et al., 2014
89	Messina Canyon, NE Sicily, Italy	1	Mediterranean Sea	Ridente et al., 2014
90	Petrace, Gioia and Mesima canyons, SW Italy	3	Mediterranean Sea	Pierdomenico et al., 2016; Casalbore et al., 2018
91	Luna and Infreschi canyons, SW Italy	2	Mediterranean Sea	Budillon et al., 2011
92	Dohrn Canyon, SW Italy	1	Mediterranean Sea	Milia, 2000
93	Golo system canyons, NE Corsica, France	4 (2)	Mediterranean Sea	Gervais et al., 2004, 2006
94	North İmralı Canyon, NW Turkey	1	Sea of Marmara	Vardar, 2019
95	Sarköy and İzmit canyons, NW Turkey	2	Sea of Marmara	Çağatay et al., 2015
96	Danube/Viteaz Canyon, SE Romania	1	Black Sea	Popescu et al., 2004

Values reported by authors have only been included for studies based on surveys that include bathymetric coverage of the entire canyon area. Average width and depth values were obtained from the literature for canyons surveyed by high-resolution bathymetry and where bathymetric data were derived from 3D seismic surveys.

### 3.2.2. Environmental attributes and external controls

For the investigation of relationships between submarine canyon geomorphology and the environmental context of the submarine canyons, attributes have been defined to record (i) canyon physiographic setting, (ii) the configuration of the canyon terrestrial catchment, continental shelf and slope, and (iii) external controls operating at the location of the canyon (Table 2 & Fig. 2).

**3.2.2.1. Physiographic setting.** The bathymetry of the canyon is characterised by the seafloor depth at its apex and mouth (Tab. 2). For canyons with several tributaries at their head, the shallowest seafloor depth has been recorded. The canyons are also classified in relation to the position of their apices relative to the shelf-break as either (i) shelf-incising,

**Table 2**

Overview and definition of the variables that have been considered in this work. Three asterisks (\*\*\*) denote values that have been calculated. Two asterisks (\*\*) denote values that have been obtained either from the literature, as reported by the original authors, measured or calculated. A single asterisk (\*) denotes values that have been retrieved from the literature, as stated by the original authors.

Code	Definition
<i>Canyon morphometrics</i>	
$L$ [km]**	streamwise length of the canyon between canyon apex and canyon mouth as measured along the canyon thalweg
$W_{max}$ [km]**	maximum width of the canyon orthogonal to the canyon length
$W_{av}$ [km]*	average canyon width over the length of the entire canyon
$D_{max}$ [m]*	maximum depth of the canyon, i.e. depth of the canyon thalweg relative to the elevation of the canyon margins
$D_{av}$ [m]*	average canyon thalweg depth over the length of the entire canyon
$SI_{av}$ [-]**	average canyon sinuosity index, i.e. ratio between the sinuous canyon length measured along its thalweg and the straight distance between canyon apex and canyon mouth
$thG_{av}$ [°]**	average canyon thalweg gradient, evaluated between canyon apex and canyon mouth
$SW_{max}$ [°]**	maximum canyon-sidewall steepness, representing the maximum value of gradient between canyon rim and canyon bottom, evaluated along the entire length of the canyon
<i>Physiographic setting</i>	
canyon apex location	the location of the canyon apex relative to the shelf break, classified as 'shelf-incising' or 'slope-confined'
$Dis_{min}$ [km]**	minimum distance between the canyon and the shoreline
$SD_{min}$ [m]**	seafloor depth at the top of the canyon; for canyons with several tributaries at their head the shallowest seafloor depth has been recorded
$SD_{max}$ [m]**	seafloor depth at the mouth of the canyon
<i>Canyon terrestrial catchment</i>	
$L_{fls}$ [km]**	length of the river with a present-day or previous connection with the canyon, from headwater to river mouth; for canyons connected with several rivers the cumulative length has been considered
$Q_{fls}$ [km <sup>3</sup> /yr]*	mean annual discharge of the fluvial system; for canyons connected with several rivers the cumulative mean annual discharge has been considered
$A_{flsc}$ [km <sup>2</sup> ]*	size of the catchment associated with the fluvial system; for canyons connected with several rivers the maximum elevation of the combined catchment has been considered
$H_{flsc}$ [m]**	maximum elevation of the catchment area relative to sea level; for canyons connected with several rivers the elevation of the highest peak in the combined catchment has been considered
<i>Continental shelf</i>	
$W_{sh}$ [km]**	width of the shelf at the canyon location
$G_{sh}$ [°]**	average shelf gradient at the canyon location
$D_{sh}$ [m]**	shelf-break depth at the canyon; for shelf edges with variable bathymetry, the deepest point is considered
<i>Continental slope</i>	
$W_{sl}$ [km]**	width of the slope at the canyon location
$G_{sl}$ [°]**	average slope gradient between the shelf break and the slope break
$D_{sl}$ [m]**	slope-break depth at the canyon
<i>Other parameters</i>	
$Lat_{abs}$ [°]**	absolute value of the latitude of the canyon apex
source-to-sink setting	physiography of the source-to-sink system the canyon is associated with, classified as: (i) continental setting; (ii) insular setting; canyons situated in trenches between islands and continents have not been included
continental-margin type	for canyons located along continental margins, including canyons associated with islands: (i) active margin (including both convergent and transform settings); (ii) passive margin

**Table 2 (continued)**

Code	Definition
oceanographic environment	(i) open sea: canyons located in an oceanic environment with open hydrodynamic interaction with adjacent seas; exposed to oceanic gyres; (ii) semi-enclosed and enclosed sea: canyons located in a sea which is largely bounded by landmasses and therefore has no or limited hydrodynamic interaction and connection with oceans; the definition includes seas, gulfs and straits

where the canyon extends into the continental shelf, or (ii) slope-confined, where the apex of the canyon is situated below the shelf break (cf. Jobe et al., 2011; Huang et al., 2014).

**3.2.2.2. Source-to-sink-system attributes.** Relationships between the geomorphology of submarine canyons and attributes of their terrestrial catchment have been investigated for canyons with sediment connectivity to a fluvial system at present or in the past. For these canyons, descriptors of fluvial system length, mean annual fluvial discharge, catchment area and maximum catchment area elevation (Tab. 2), have been recorded. Sediment connectivity of a submarine canyon with a fluvial source is defined based on the following three criteria:

- (i) *The submarine canyon displays a present connection with a fluvial system.* This includes canyons fronting a river mouth, canyons for which across-shelf sediment transport from a fluvial outlet has been inferred by authors, e.g. from sedimentary structures on the seafloor as sediment waves (e.g. Puig et al., 2017), and canyons connected to up-dip subenvironments, such as shelf channels and tributary canyons, which are physically connected with a fluvial system.
- (ii) *The submarine canyon was connected to a river in the past.* This includes canyons that might not currently be connected to a fluvial system, e.g. due to present-day sea-level highstand conditions or to river-mouth shift of natural or anthropogenic cause, but that are known to have been connected in the past to a river (e.g. Sweet et al., 2020).
- (iii) *The canyon apex is located within 5 km of a fluvial outlet.* This criterion has been considered in view of the typical length-scale over which sand tends to be distributed to submarine canyons by rivers that lack a bathymetric connection to the canyons (see Sweet and Blum, 2016).

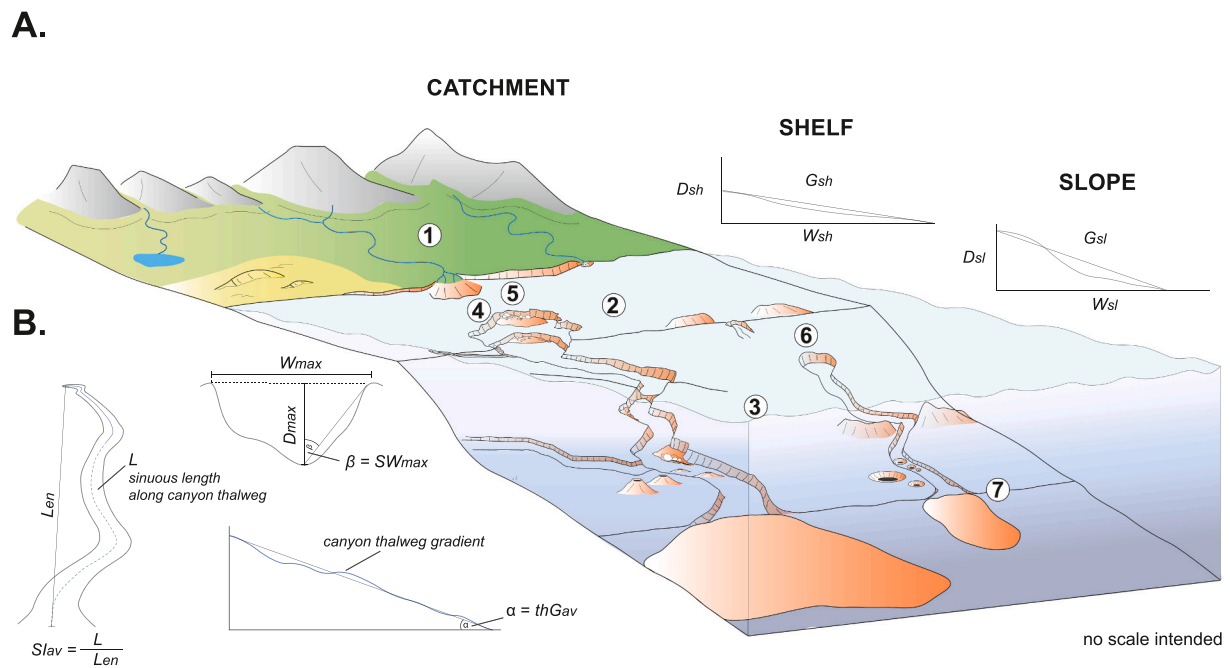
For canyons linked with several rivers, their cumulative length, mean annual fluvial discharge and catchment area have been recorded, to enable comparison with canyons fed by single fluvial systems. For investigation of relationships between canyon geomorphology and maximum elevation of the terrestrial catchment, the elevation above mean sea level of the highest point in the combined catchment has been recorded.

The continental shelf and slope hosting the canyons have been described in terms of width, average gradient and depth.

**3.2.2.3. Continental-margin type.** The source-to-sink system has been classified as being associated with either a passive or a tectonically active continental margin, the latter comprising canyons along both convergent and transform plate boundaries, following the continental-margin classification of Harris et al. (2014; see their Fig. 2).

**3.2.2.4. Source-to-sink setting.** The source-to-sink setting associated with the studied canyons has been classified on whether the terrestrial catchment, shelf and slope are associated with continental landmasses (continental setting) or an island (insular setting). Canyons which could not be unambiguously assigned to a setting have not been included.





**Fig. 2.** A. Attributes of the source-to-sink system and physiographic setting investigated in the study: 1. Terrestrial catchment: fluvial system length, average annual fluvial discharge, catchment size, maximum elevation. 2. Shelf configuration: width, depth, average gradient. 3. Slope configuration: width, depth, average gradient. 4. Canyon-apex location relative to the shelf-break. 5. Minimum distance to shoreline. 6. Seafloor depth at the top of the canyon. 7. Seafloor depth at the canyon mouth. B. Key canyon morphometric parameters considered in the study:  $L$  = canyon length along thalweg  $L_{en}$  = canyon length along endpoints;  $W_{max}$  = maximum canyon width;  $D_{max}$  = maximum canyon depth;  $SL_{av}$  = average canyon sinuosity index;  $thG_{av}$  = average canyon thalweg gradient;  $SW_{max}$  = maximum canyon sidewall steepness.

**3.2.2.5. Oceanographic environment.** To investigate the possible controls exerted by hydrodynamic processes that vary with scale and marine water-mass confinement, and potential relationships between canyon morphometric parameters and the scale and degree of confinement of the seas where they occur, canyons are classified with respect to their oceanographic environment. To this end, two groups have been distinguished: (i) open seas, which comprise the World's oceans and experience hydrodynamic interactions with adjacent seas; they may be characterised by the occurrence of oceanic gyres; (ii) semi-enclosed and enclosed seas, which are largely bounded by landmasses and are therefore characterised by a limited hydrodynamic interaction with the oceans or seas with which they are connected; this second class includes seas, gulfs and straits.

**3.2.2.6. Latitude.** The latitudinal positions of canyon heads are recorded as absolute values for both hemispheres. For the investigation of latitude-related climatic influences on processes affecting canyon geomorphology, latitude values have been assigned to categories that relate to major climate belts, i.e., into tropical (corresponding to latitudes between  $0^\circ$  and  $23.5^\circ$ ), temperate (between  $23.5^\circ$  and  $66.5^\circ$ ), and polar zones (corresponding to latitudes higher than  $66.5^\circ$ ). This simplified approach has been implemented for the following reasons: (i) existing climate classification schemes are commonly based on parameters of the terrestrial catchment and would therefore have limited applicability to canyons that do not receive significant fluvial discharge or none at all; moreover, climatic conditions in the marine environment are commonly not considered in these schemes; (ii) climate histories, including temperature and precipitation, would have to be reconstructed for both the present and the past to permit a consistent analysis of their impact on canyon evolution; this becomes particularly challenging for submarine canyons associated with large source-to-sink systems; (iii) the age of inception of the majority of the canyons in the present study is poorly constrained, so that climate histories cannot be matched closely to canyon age.

### 3.3. Statistical analysis

Relationships between canyon morphometric parameters and descriptors of physiographic setting and external controlling factors have been investigated by statistical analyses.

- (i) Descriptive statistics of frequency distributions of canyon morphometric parameters are evaluated for classes of: canyon-apex location relative to the shelf-break, continental-margin type, source-to-sink setting, oceanographic environment, and latitudinal position of the canyon apex or head. Comparisons between distributions of values in canyon groups are undertaken.
- (ii) Statistical testing has been used to evaluate whether differences in mean values of canyon morphometrics between groups of canyons are statistically significant. For assessment across two groups, two-sample t-tests have been conducted, whereas differences in mean values between more than two canyon groups have been assessed by means of one-way analysis of variance (ANOVA). To test datasets with heteroscedastic distributions, Welch's t-test and Welch's ANOVA have been used throughout. Test statistics, degrees of freedom (DF) and P-values are presented for all tests. Results with p-values  $\leq 0.01$  are reported as statistically significant. Prior to the analyses, a logarithmic variable transformation is applied to skewed frequency distributions.
- (iii) Correlation analysis has been applied to investigate pairwise relationships between the studied parameters from the individual values obtained for each studied canyon. The strength and sign of correlation between two parameters is quantified by Pearson's correlation coefficient ( $r$ ), to reveal linear relationships, and by Spearman's rank correlation coefficient ( $r_s$ ), to reveal monotonic relationships. A correlation is considered statistically significant for p-values  $\leq 0.01$ .

Although statistical analyses have been performed for any number of

readings (N), the results are commonly presented and discussed when  $N \geq 15$ ; it is explicitly stated when  $N < 15$ .

All statistical analyses have been undertaken in Minitab 19.

### 3.4. Limitations of the study

Some of the key limitations of this study can be summarised as follows.

- (i) In studies of submarine canyons there exists some geographic and thematic bias, as recognised by [Matos et al. \(2018\)](#), and some of that bias may have been inherited by this work. For example, logistic, financial and environmental challenges to investigating submarine canyons in polar regions might explain the relative scarcity of local- and regional-scale case studies of submarine canyons in the Arctic and Antarctica. Also, research efforts might be more focused on specific classes of canyons: for example, larger submarine canyons might be of particular interest for studies of marine habitats or as modern analogues for ancient systems in hydrocarbon exploration. Despite this, an effort has been made to compile a globally representative dataset of case studies of submarine canyons associated with different types of environmental settings (see [Fig. 1](#) & [Table 1](#)). The study also incorporates 12 canyon studies published after 2016, which were not considered by [Matos et al. \(2018\)](#) in their analysis.
- (ii) The scale of slope channel forms recognised in the case studies depends on data resolution, which sets the limit of the smallest mappable geomorphic features, and affects the precision of measurements. Due to heterogeneity in data types, some variability in resolution is expected.
- (iii) As in any metastudy, erroneous data reported in the primary data sources may have been inadvertently included in the database. However, all reasonable measures have been taken to ensure data accuracy.
- (iv) Although this study considers many environmental factors that may act as controls on canyon geomorphology, some relationships might arise from covariance of such factors with one or several parameters that have not been included in our analyses.
- (v) Shelf-margin and base-of-slope depths of continental margins lacking distinct morphological breaks at the shelf-slope transition and/or in the base-of-slope region are difficult to determine precisely. As such, these attributes may have not been reported in the literature, and have not been included in the current dataset.
- (vi) Despite the ability afforded by studies of modern canyons to constrain physiographic setting, external factors and process-response relationships, measurements of the physical characteristics of canyons and their settings only represent snapshots of the temporal evolution of the studied forms.
- (vii) The continental-margin type, source-to-sink setting, and oceanographic environment constitute factors that apply to the entire extent of the studied canyons, and thus allow consistent grouping. In contrast, along their length, some submarine canyons might stretch across two latitudinal zones. The position of the canyon apex relative to the shelf break can be variable over time, but incision of the shelf by the canyon does not per se represent a more mature evolutionary stage of the canyon. Some canyons that are presently slope-confined might have had a physical connection to the shelf in the past: their canyon heads and proximal parts may have been backfilled ([Pratson et al., 2007](#)) or may have prograded basinwards ([Mauffrey et al., 2015](#)). This must be considered in analyses of frequency distributions of canyon morphometrics across slope-confined and shelf-incising forms.

## 4. Scaling relationships between canyon morphometrics

### 4.1. Observations

Correlation strengths between canyon morphometric parameters are highly variable, with only some correlations being strong and statistically significant ([Figs. 3 & 4 a-o](#)).

Maximum dimensions of the studied canyons are moderately correlated with each other ([Fig. 4a-c](#)). Strong relationships that are statistically significant exist for average canyon width with maximum width ([Fig. 3](#)), length ([Fig. 4a](#)) and maximum depth ([Fig. 4c](#)), and for the latter with average depth ([Fig. 3](#)). In addition, modest significant scaling is demonstrated for maximum width and average depth ([Fig. 4c](#)). In contrast, correlations of average canyon depth with canyon length ([Fig. 4b](#)) and average canyon width ([Fig. 4c](#)) are weak and not significant. Strong correlations between length and canyon width, and no correlation between canyon length and average depth, are also observed in the dataset by [Harris et al. \(2014\)](#) ([Fig. 4p&q](#)).

Average canyon sinuosity shows significant, respectively modest and moderate, positive correlations with canyon length ([Fig. 4d](#)) and average canyon depth ([Fig. 4f](#)), and modest correlations with maximum canyon width ([Fig. 4e](#)). The negative correlation between sinuosity and average canyon thalweg gradient is significant but rather weak ([Fig. 4m](#)), whereas no correlation is seen between sinuosity and maximum canyon sidewall steepness ([Fig. 4n](#)).

The average canyon thalweg gradient demonstrates moderate negative correlation with canyon length ([Fig. 4g](#)) and weak negative correlation with maximum canyon width ([Fig. 4h](#)), both of which are statistically significant. The positive moderate correlation between thalweg gradient and average canyon depth is not statistically significant ( $N = 12$ ; [Fig. 4i](#)). No correlation exists between thalweg gradient and either average width ([Fig. 4h](#)) and maximum sidewall steepness ([Fig. 4o](#)).

Positive, modest and statistically significant relationships are seen between maximum canyon sidewall steepness and both maximum canyon width ([Fig. 4k](#)) and depth ([Fig. 4l](#)), whereas the maximum canyon sidewall steepness is weakly correlated with canyon length ([Fig. 4j](#)).

### 4.2. Interpretations

Correlations between pairs of canyon morphometric parameters suggest that both considered canyon characteristics may be affected by the same process or controlling factors.

In some cases, correlations may arise – either in part or fully – due to covariance with other parameters, and this may be inherent in the definition of the parameters themselves. For example, more sinuous canyons tend to have longer streamwise canyon length for a given slope extent, whereas deeper channel forms are expected to have steeper margins.

In addition, some canyon morphometrics appear to be more strongly related to certain environmental controls; this is discussed in [sections 5, 6 and 7](#).

#### 4.2.1. Sedimentary processes

Because the effects of sedimentary processes on canyon evolution depend primarily on the sediment volumes they mobilise, their erosive strength and their areal extent, sedimentary processes can affect canyon morphometrics in different ways, at different locations along a canyon and even during the same event (e.g. [Su et al., 2020](#)). The ability of sediment gravity flows and slope failures to trigger one another (e.g. [Pratson and Coakley, 1996](#); [Bernhardt et al., 2015](#)) and the common transition of the latter into the former (e.g. [Puig et al., 2014](#)) makes it difficult to differentiate between the relative importance of these processes in shaping canyon geomorphology. As a consequence, it may not be possible to establish causal links between intra-canyon-scaling

**Pearson's correlation coefficient r**

L								
W <sub>max</sub>	0.529							
W <sub>av</sub>	0.847	0.801						
D <sub>max</sub>	0.544	0.769	0.813					
D <sub>av</sub>	0.158	0.472	0.345	0.950				
SI <sub>av</sub>	0.467	0.418	0.238	0.297	0.478			
thG <sub>av</sub>	-0.476	-0.343	-0.051	-0.211	0.668	-0.336		
SW <sub>max</sub>	0.115	0.446	-0.238	0.350	n.e.d.	0.146	0.159	
	L	W <sub>max</sub>	W <sub>av</sub>	D <sub>max</sub>	D <sub>av</sub>	SI <sub>av</sub>	thG <sub>av</sub>	SW <sub>max</sub>

**p-value**

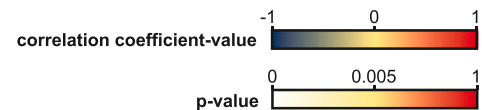
L								
W <sub>max</sub>	≤0.001							
W <sub>av</sub>	≤0.001	≤0.001						
D <sub>max</sub>	≤0.001	≤0.001	≤0.001					
D <sub>av</sub>	0.263	0.006	0.016	≤0.001				
SI <sub>av</sub>	≤0.001	≤0.001	0.058	0.034	≤0.001			
thG <sub>av</sub>	≤0.001	0.002	0.806	0.090	0.018	0.004		
SW <sub>max</sub>	0.356	≤0.001	0.375	0.006	n.e.d.	0.432	0.341	
	L	W <sub>max</sub>	W <sub>av</sub>	D <sub>max</sub>	D <sub>av</sub>	SI <sub>av</sub>	thG <sub>av</sub>	SW <sub>max</sub>

**Spearman's rank correlation coefficient rs**

L								
W <sub>max</sub>	0.621							
W <sub>av</sub>	0.613	0.814						
D <sub>max</sub>	0.653	0.733	0.821					
D <sub>av</sub>	0.176	0.333	0.277	0.958				
SI <sub>av</sub>	0.536	0.380	0.148	0.347	0.542			
thG <sub>av</sub>	-0.660	-0.363	0.015	-0.141	0.631	-0.363		
SW <sub>max</sub>	0.325	0.382	-0.268	0.439	n.e.d.	0.068	0.290	
	L	W <sub>max</sub>	W <sub>av</sub>	D <sub>max</sub>	D <sub>av</sub>	SI <sub>av</sub>	thG <sub>av</sub>	SW <sub>max</sub>

**p-value**

L								
W <sub>max</sub>	≤0.001							
W <sub>av</sub>	≤0.001	≤0.001						
D <sub>max</sub>	≤0.001	≤0.001	≤0.001					
D <sub>av</sub>	0.212	0.063	0.056	≤0.001				
SI <sub>av</sub>	≤0.001	≤0.001	0.244	0.013	≤0.001			
thG <sub>av</sub>	≤0.001	0.001	0.940	0.258	0.028	0.002		
SW <sub>max</sub>	0.007	0.003	0.316	≤0.001	n.e.d.	0.716	0.077	
	L	W <sub>max</sub>	W <sub>av</sub>	D <sub>max</sub>	D <sub>av</sub>	SI <sub>av</sub>	thG <sub>av</sub>	SW <sub>max</sub>



**Fig. 3.** Heat maps of correlations of canyon morphometric parameters for canyons of the study displaying values of Pearson's correlation coefficient r and Spearman's rank correlation coefficient rs, and their respective p-values. L = canyon length; W<sub>max</sub> = maximum canyon width; W<sub>av</sub> = average canyon width; D<sub>max</sub> = maximum canyon depth; D<sub>av</sub> = average canyon depth; SI<sub>av</sub> = average canyon sinuosity index; thG<sub>av</sub> = average canyon thalweg gradient; SW<sub>max</sub> = maximum canyon sidewall steepness. n.e.d. = not enough data to facilitate statistical analyses.

relationships and sediment-transport mechanisms. Nevertheless, observed scaling between some canyon morphometric parameters suggests that the influence of one or several controlling factors tends to be prevalent, giving rise to canyon geomorphologic characteristics that are recognizable on a global scale despite specific regional or local conditions.

Canyon enlargement can be driven by active erosive processes, such as primary erosion by sediment gravity flows passing through the canyon (e.g. Li et al., 2021) or by slope failure within the canyon and on the adjacent slope (e.g. Post et al., 2022), but also by accretion of the adjacent slope or of ridges between canyons, which may be caused by along-slope currents (e.g. Rona, 1970), by background sedimentation or spillover of sediment gravity flows passing through canyons (e.g. Straub and Mohrig, 2009; Armitage et al., 2010), or due to primary carbonate production (e.g. Shepard, 1972; Tournadour et al., 2017). By contrast, intra-canyon aggradation, e.g. by backfilling (Cronin et al., 2005), sediment accumulation in canyon heads (e.g. Walsh et al., 2007) and hemipelagic sedimentation (e.g. Jobe et al., 2011) weaken the effect of erosive processes on positive scaling relationships in canyon morphometry, for example by shortening canyons and decreasing their depths.

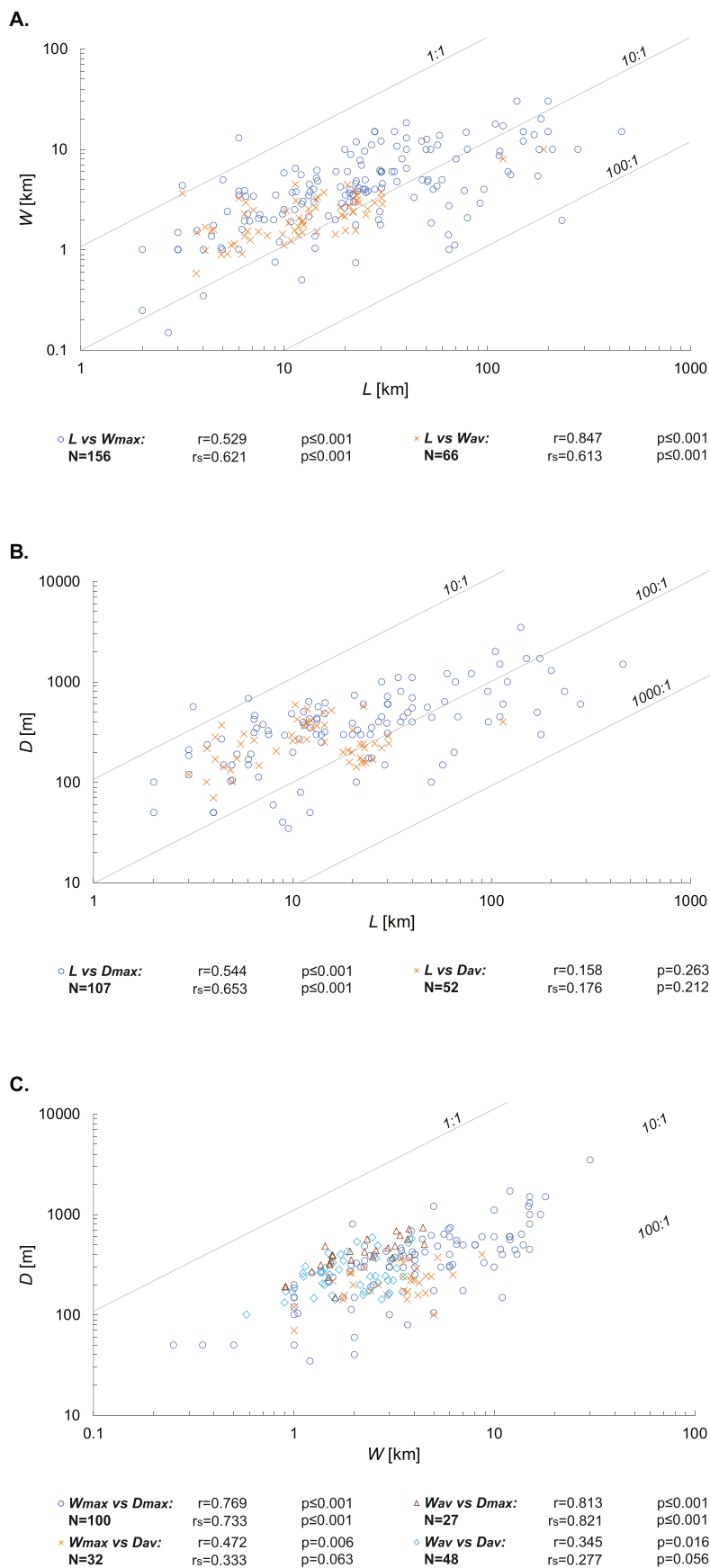
The fact that these processes can variably modify individual canyon morphometric parameters is likely reflected in the observed scaling between maximum and average canyon dimensions. The rather strong scaling of canyon length with average canyon width may be linked to the ability of down-canyon flows to maintain their erosive behaviour beyond the canyon mouth. The moderate scaling of canyon length with maximum width might be related to the fact that lateral slope failures lead to local widening of the canyon over the excavated area, but may only increase canyon length where the mobilised sediment volume – which might also comprise intra-canyon sediment sources – is sufficient to extend the canyon beyond its present mouth. This may arise, for example, by breaching of intra-slope structural highs or by facilitating the progradation of the continental rise. Retrograde slope failures act as

a primary cause of canyon lengthening (e.g. Orange et al., 1994; Pratson and Coakley, 1996; Pratson et al., 2007) and might cause the local widening of canyons in their proximal parts in correspondence of slump scars, where these are intercepted (e.g. Mulder et al., 2012a, 2012b). Relatively strong scaling of maximum depth with maximum and average width in the sampled canyons may in part reflect simultaneous canyon-margin aggradation and intra-canyon erosion. The positive scaling between maximum width and maximum canyon sidewall steepness can in part be explained by lateral canyon-slope failures causing a local increase in canyon width and canyon sidewall steepness, and by thalweg erosion.

**4.2.2. Hydrodynamic processes**

Marine hydrodynamic processes on the shelf and slope can variably influence canyon geomorphology: (i) by their direct effect on sedimentary processes within the canyon itself, and (ii) by exerting control on sediment supply from terrestrial, intra-shelf and slope sources to canyons, which in turn can impact intra-canyon sedimentary processes.

Hydrodynamic processes that have been inferred to facilitate sediment supply to submarine canyons include tides (e.g. Mountjoy et al., 2014), long-lived longshore drifts (e.g. Normark et al., 2009; Smith et al., 2018), slope currents (e.g. Wang et al., 2018), high-energetic waves (e.g., solitary waves, Yin et al., 2019; storm waves, Sequeiros et al., 2019), and dense shelf-water cascading (e.g. Canals et al., 2006; Puig et al., 2014, and references therein; Gales et al., 2021). The processes are highly variable in terms of frequency, magnitude, duration and area of influence, and these factors affect both the volume and grain size of sediment sourced to canyons. Intra-canyon erosion, remobilisation and transport of sediment have been linked to tidal (e.g. Liu and Yin, 2004) and unidirectional oceanic currents (e.g. Itoh et al., 2010) passing through a canyon, and to the focussing of internal waves in both the shallower parts of shelf-incising canyons (e.g. Smith et al., 2018) and at greater water depths in canyons confined within the slope (e.g. Wang et al., 2022). Hence, the influence of marine hydrodynamic processes on



**Fig. 4.** a-q: A.-O. Scatterplots of morphometric parameters of the studied canyons. P.&Q. Scatterplots of canyon length with width (P) and average depth (Q) plotted from the dataset of Harris et al. (2014) with an overlay of data from this study for comparison. N = number of observations; r = Pearson's correlation coefficient;  $r_s$  = Spearman's rank correlation coefficient. See Fig. 3 for key to abbreviations.

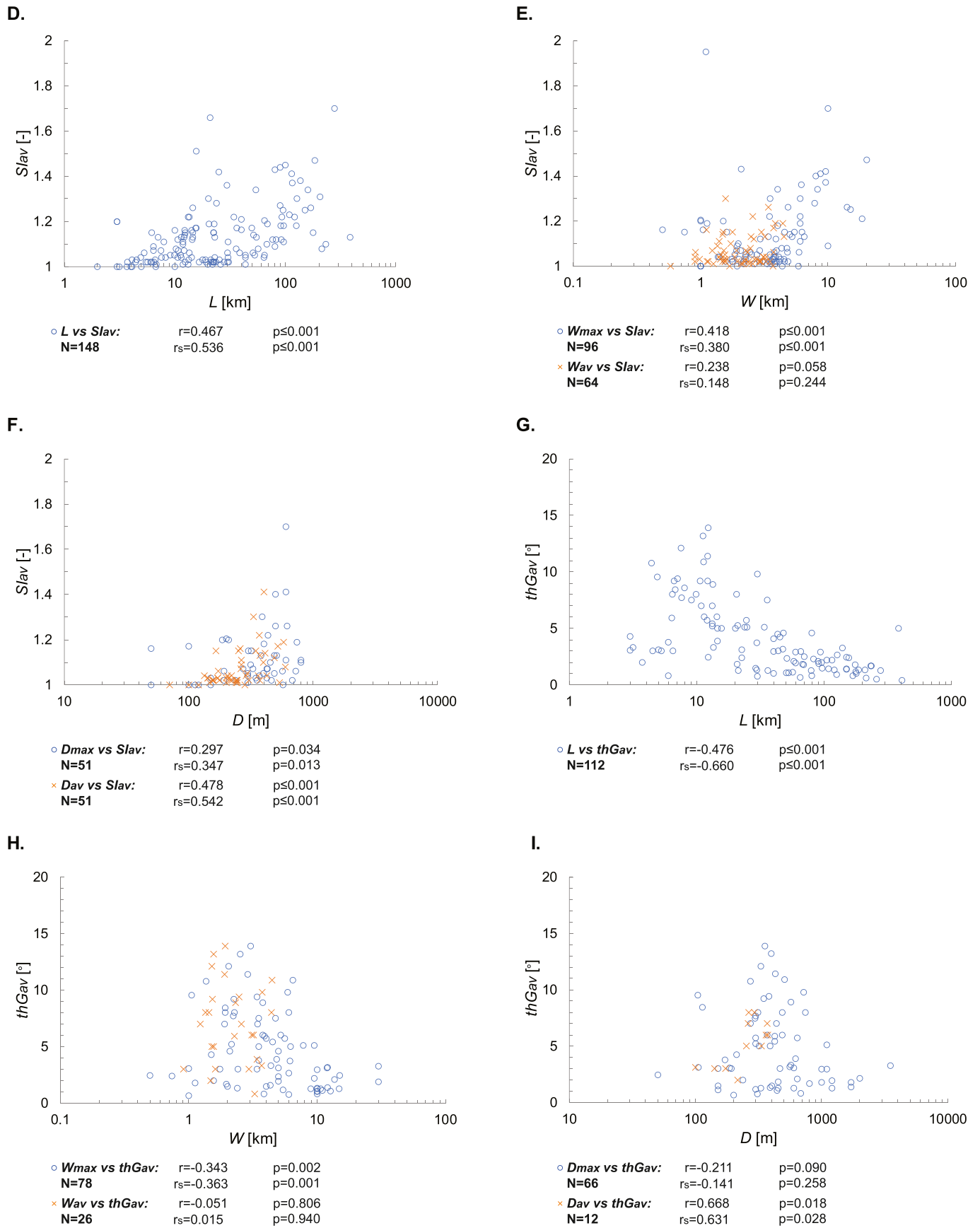


Fig. 4. (continued).

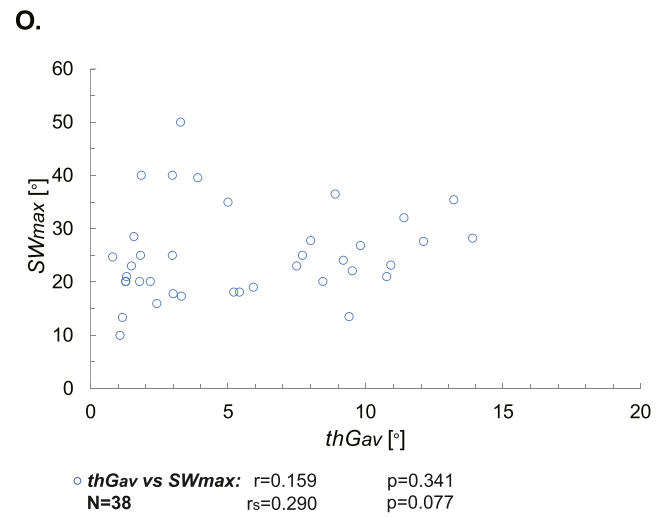
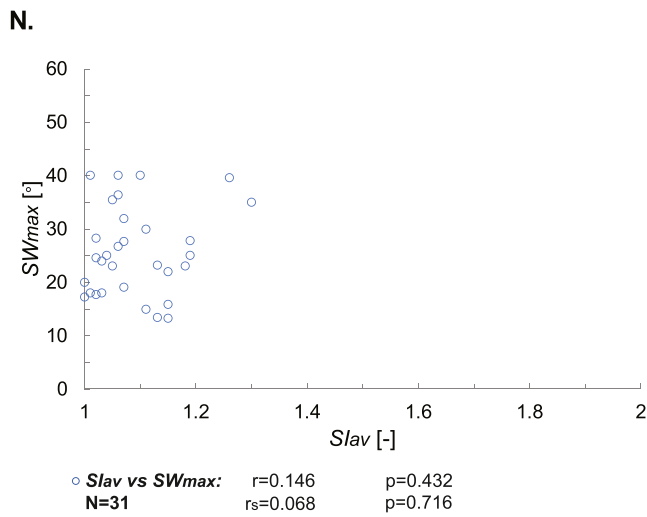
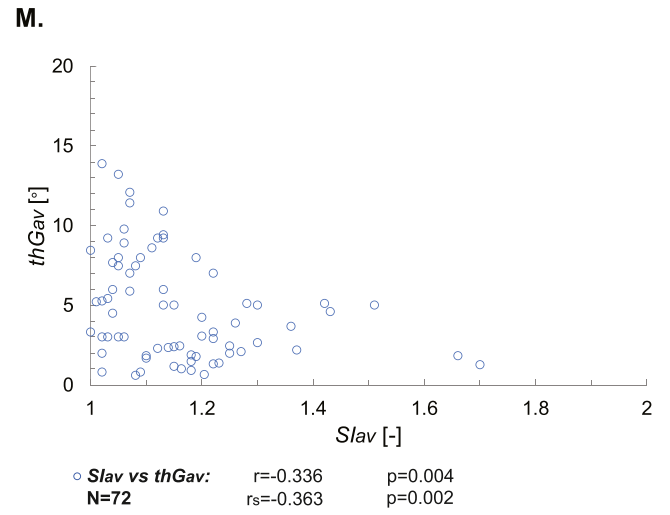
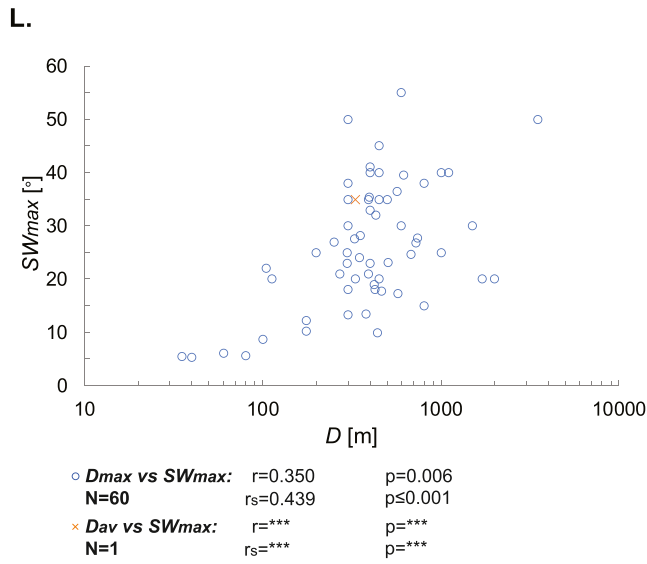
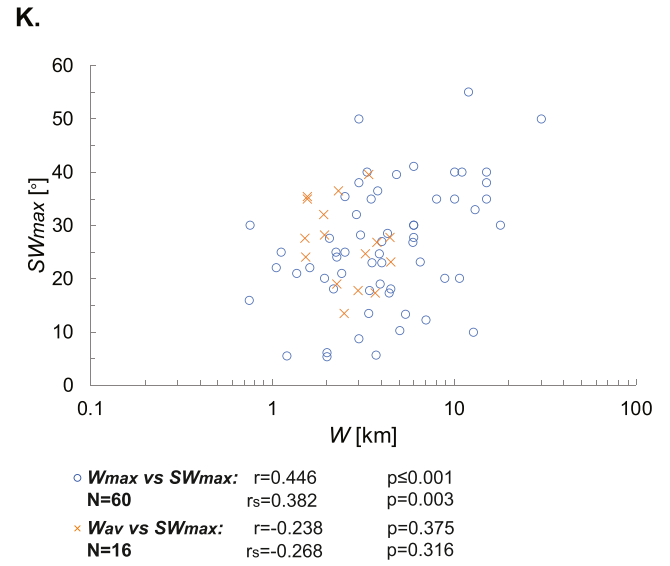
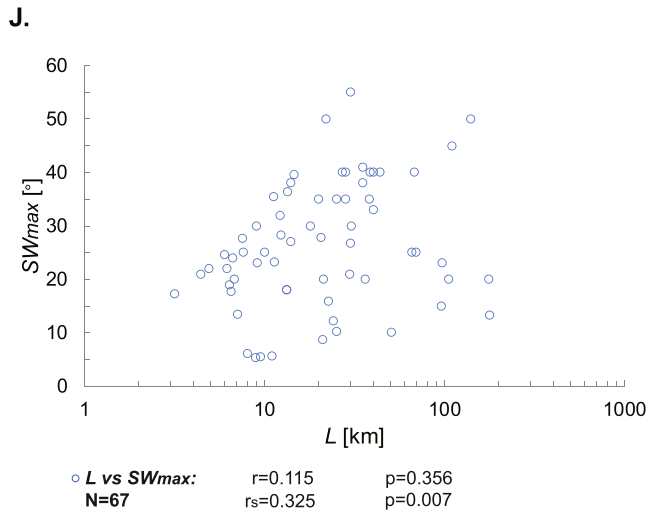


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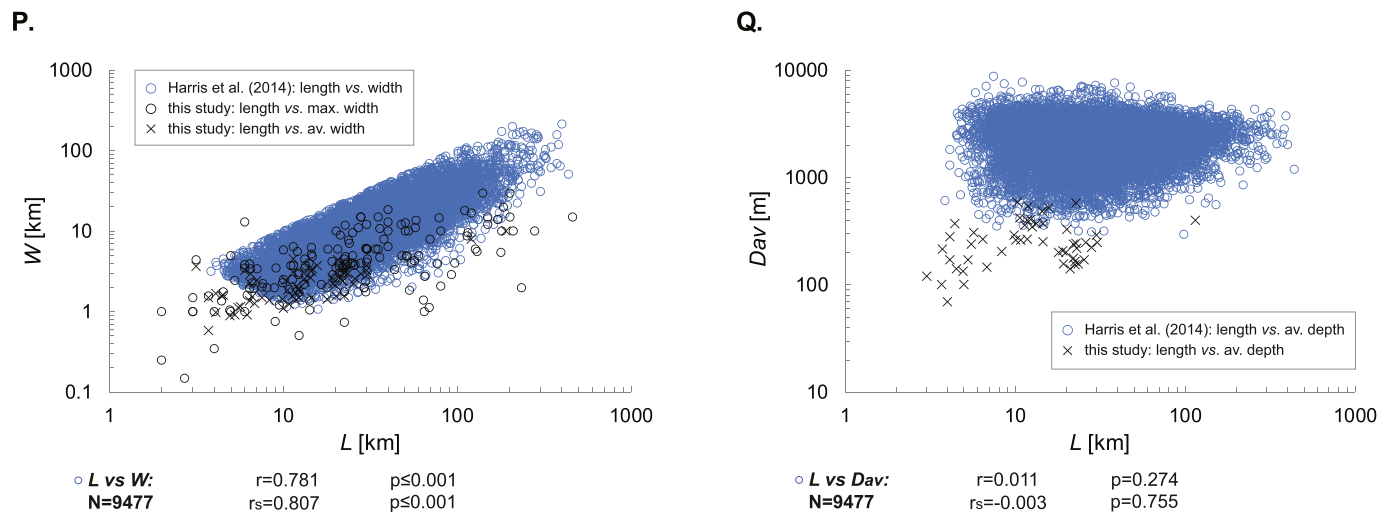


Fig. 4. (continued).

canyon geomorphology is complex and might both amplify or weaken the impact of sedimentary processes on the strength of scaling relationships between canyon morphometric attributes.

For example, canyons hosted on continental margins with strong oceanic currents might experience less frequent canyon-margin failures and reduced aggradation, due to the ability of such currents to inhibit sedimentation along canyon margins (e.g. Green, 2011). As a result, the impact of axial sediment gravity flows on scaling in canyons might be, to a lesser degree, overprinted by lateral failure in these canyons. On the contrary, currents that can lead to sediment accumulation along canyon margins may strengthen the scaling between canyon depth, width and margin slopes (see section 4.2.1). Moreover, the complex influence of slope currents and internal tidal waves on canyon geomorphology, related to the co-occurrence of intra-canyon erosional and depositional processes including canyon flushing and canyon-wall failure (see Wang et al., 2022) might variably affect the strength in scaling between canyon morphometrics.

#### 4.2.3. Structural controls

Structural controls might affect canyon geomorphology by their influence on pre-existing and developing seafloor topography, which might have contributed to the weakening of some of the relationships between canyon morphometric attributes. For example, where fault and diapiric structures form part of the canyon walls or are in vicinity of the canyon margin, they can steepen the canyon sidewalls (e.g. Yu and Chang, 2002; Bernhardt et al., 2015), and might overprint the effect of concurrent intra-canyon erosion by down-canyon sediment flows and canyon sidewall failure on canyon width, depth and sidewall steepness and the strength of their mutual scaling. In addition, emerging topography, generated for example by coral reef growth (e.g. Puga-Bernabéu et al., 2011) or diapiric uplift (e.g. Chiang et al., 2012), might cause flow deceleration, flow deflection, flow stripping and/or grain size segregation, which in turn might weaken the erosional effect of flows further down-canyon. Similarly, substrate heterogeneity arising from pre-existing structural features or buried canyons might cause spatial variations in substrate erodibility. In turn, the erodibility of canyon floors or walls might be diminished or enhanced over the affected area, which can promote an overall irregular canyon geometry, and variably impact the average canyon sinuosity and canyon thalweg gradient.

#### 4.2.4. Biogenic processes

The effect of the colonization of canyon walls and margins by marine fauna on canyon-wall stability has received limited attention in the literature (e.g. Shepard, 1981; Eittreim et al., 1982; Carlson and Karl,

1984, and references therein). Depending on factors such as nature of substrate, degree of bioturbation, filling and cementation, the canyon sidewall stability might be increased or decreased by bioturbation. Similarly, vegetation cover in proximal parts of canyons, specifically by marine flora in the photic zone, might reduce the erodibility of canyon slopes. The resulting variability in the erodibility of canyon walls and apices might affect the scaling relationships between canyon length, width and sidewall steepness. Thus, biogenic processes might constitute a controlling factor on scaling in canyon morphology. Future research is needed to enhance our understanding of the impact of biota on canyon geomorphology.

## 5. Relationships between canyon morphometric parameters and attributes of the physiographic setting

### 5.1. Distance between canyon and shoreline

#### 5.1.1. Observations

The minimum distance between the canyon apex and the shoreline is not correlated to any of the canyon morphometric parameters except for the average canyon width (Figs. 5 & 6a-f), for which modest but statistically significant positive correlation is seen (Fig. 6b). However, in the assessment of a relationship with average canyon width, the average widths of canyons with a distance to a continent or island of  $\leq 25$  kilometres could not be evaluated.

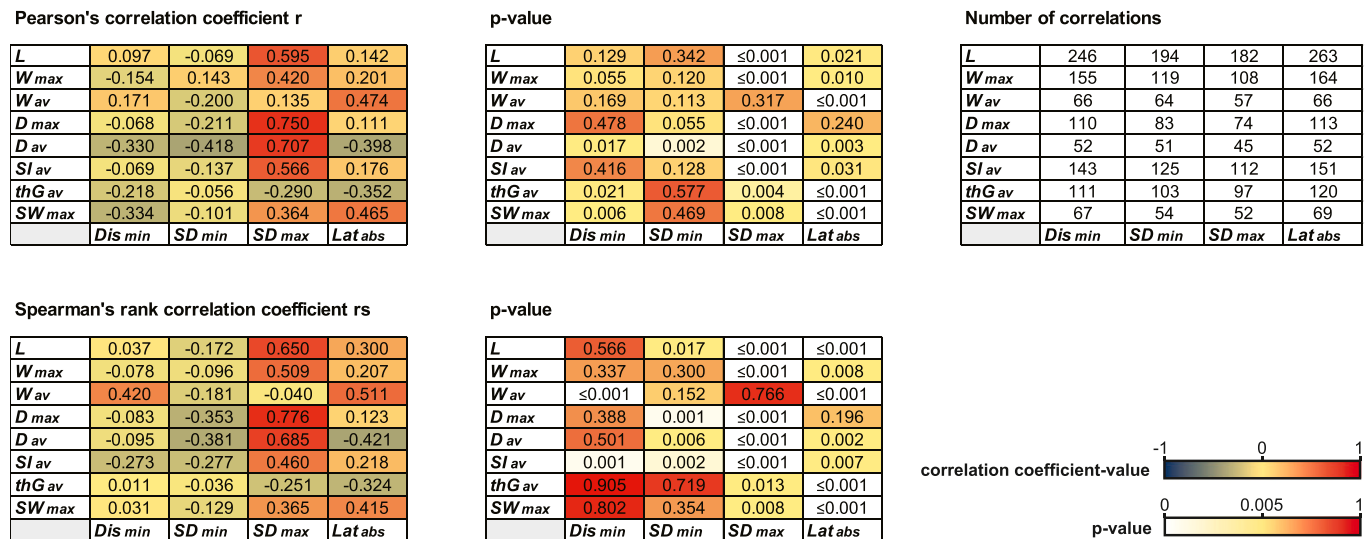
#### 5.1.2. Interpretations

Although the distance of the canyon to the shoreline plays a role in sediment distribution from fluvial sources across shelves and slopes (section 6.1), the results show that relationships between the distance of the canyon to the shoreline and overall canyon geomorphology are weak. It can thus be inferred that the distance to the shoreline itself is not a major factor, relative to others.

### 5.2. Canyon bathymetry

#### 5.2.1. Observations

**5.2.1.1. Seafloor depth at the canyon apex.** Most canyon morphometrics correlate poorly with seafloor depth at the canyon apex (Figs. 5 & 7a-f). Modest negative correlations are seen with average canyon depth, and a weak negative relationship with maximum canyon depth, both of which are statistically significant (Fig. 7c). A weak but significant negative correlation is also displayed with average canyon sinuosity (Fig. 7d).



**Fig. 5.** Heat maps for correlations of canyon morphometrics with the physiographic setting displaying values of Pearson's correlation coefficient  $r$  and Spearman's rank correlation coefficient  $r_s$ , and their respective  $p$ -values.  $L$  = canyon length;  $W_{max}$  = maximum canyon width;  $W_{av}$  = average canyon width;  $D_{max}$  = maximum canyon depth;  $D_{av}$  = average canyon depth;  $SI_{av}$  = average canyon sinuosity index;  $thG_{av}$  = average canyon thalweg gradient;  $SW_{max}$  = maximum canyon sidewall steepness;  $Dis_{min}$  = minimum distance between the canyon and shoreline;  $SD_{min}$  = minimum seafloor depth at the canyon apex;  $SD_{max}$  = maximum seafloor depth at the canyon mouth;  $Lat_{abs}$  = absolute value of the latitude of the canyon apex.

**5.2.1.2. Seafloor depth at the canyon mouth.** The seafloor depth at the canyon mouth tends to correlate significantly with all investigated canyon morphometric parameters except for average canyon width (Figs. 5 & 8a-f). Moderate positive correlations are seen with canyon length (Fig. 8a), maximum canyon width (Fig. 8b), both maximum and average canyon depth (Fig. 8c), and with average canyon sinuosity (Fig. 8d), whereas correlations with maximum canyon sidewall steepness are weaker (Fig. 8f). In contrast, a weak negative correlation is seen with the average canyon thalweg gradient (Fig. 8e).

**5.2.2. Interpretations**

**5.2.2.1. Seafloor depth at the canyon apex.** No clear relationships are seen between canyon geomorphology and the seafloor depth at the apex of the canyon, except for canyon depth. Data on maximum and average canyon dimensions demonstrate that large canyons can develop regardless of the seafloor depth at the canyon apex. The results indicate that the absolute canyon-apex depth does not necessarily relate to controlling factors influencing canyon geomorphology, such as a connection to sediment sources (section 6.1), the hydrodynamic regime (section 4.2.2) or structural controls (section 4.2.3). Although the canyon length increases with retrograde erosion at the canyon head, which leads to progressive shallowing of the canyon apex, the bathymetry of the basin ultimately determines the canyon length (section 6.3). The tendency of canyons to be deeper when their apex is shallower might reflect how canyon deepening may be facilitated by erosive sediment gravity flows linked to the progressive retrogradation of the canyon, which can enhance sediment delivery from terrestrial and intrashelf sources and from sediment remobilisation within the canyon. Weak scaling between canyon morphometric parameters and canyon-apex depth might also reflect how substrate lithology and seafloor gradients, which affect canyon morphodynamics and the magnitude and frequency of mass-wasting processes, vary systematically with depth (e.g. Harris et al., 2014; Diesing, 2020).

**5.2.2.2. Seafloor depth at the canyon mouth.** The results suggest that canyons reaching greater depths tend to have greater maximum dimensions and average depths, but not average widths. The observed increase in maximum canyon width and depth with increasing seafloor

depth at the canyon mouth may be linked to the widening and deepening of canyons by turbidity currents in the region of the canyon mouth as a response to a decrease in slope gradient (e.g. Brunt et al., 2013). In addition, results of physical experiments suggest that, in long canyons, the upwelling of along-slope currents via the canyon mouth creates cyclonic eddies in the mouth region (Waterhouse et al., 2009). This mechanism might cause lateral erosion at the canyon margins and might promote intra-canyon erosion in the canyon-mouth area.

Our results also indicate that canyons reaching into deeper waters tend to be more sinuous, which might reflect an increased impact of seafloor relief on canyon geomorphology with progressive extension of the canyon across the continental slope. For example, canyons might become more sinuous and longer where their pathways are deflected and redirected by topographic highs (e.g. Micallef et al., 2014) and intraslope depressions (e.g. Bourget et al., 2010). The effect of seafloor topographic variability might also in part explain the positive scaling of maximum width with seafloor depth, in view of how longer canyons are more likely to have a larger number of sections displaying local widening in planform, for example where intraslope depressions are incorporated in the canyon.

For maximum canyon sidewall steepness, the positive scaling with seafloor depth at the canyon mouth might in part reflect how the studied canyons located in open seas tend to have steeper canyon margins than those in semi-enclosed and enclosed seas (section 7.4), and continental slopes in open oceanic settings reaching greater depths.

**5.3. Latitudinal position of the canyon apex**

The canyons in our study cover a latitudinal range between 1° and 72° degrees. However, data on high-latitude canyons is limited to 15 examples from the NW Norwegian continental margin and the Barrow Canyon in the NE Chukchi Sea; polar canyons along the Antarctic margin are notably lacking in the dataset (see section 3.3).

**5.3.1. Observations**

For absolute values of latitude of the canyon apex and canyon morphometric parameters, correlations are weak to moderate in strength (Figs. 5 & 9a-f). Moderate positive correlation exists between latitude and average canyon width (Fig. 9b), and modest negative correlations between latitude and both average depth (Fig. 9c) and



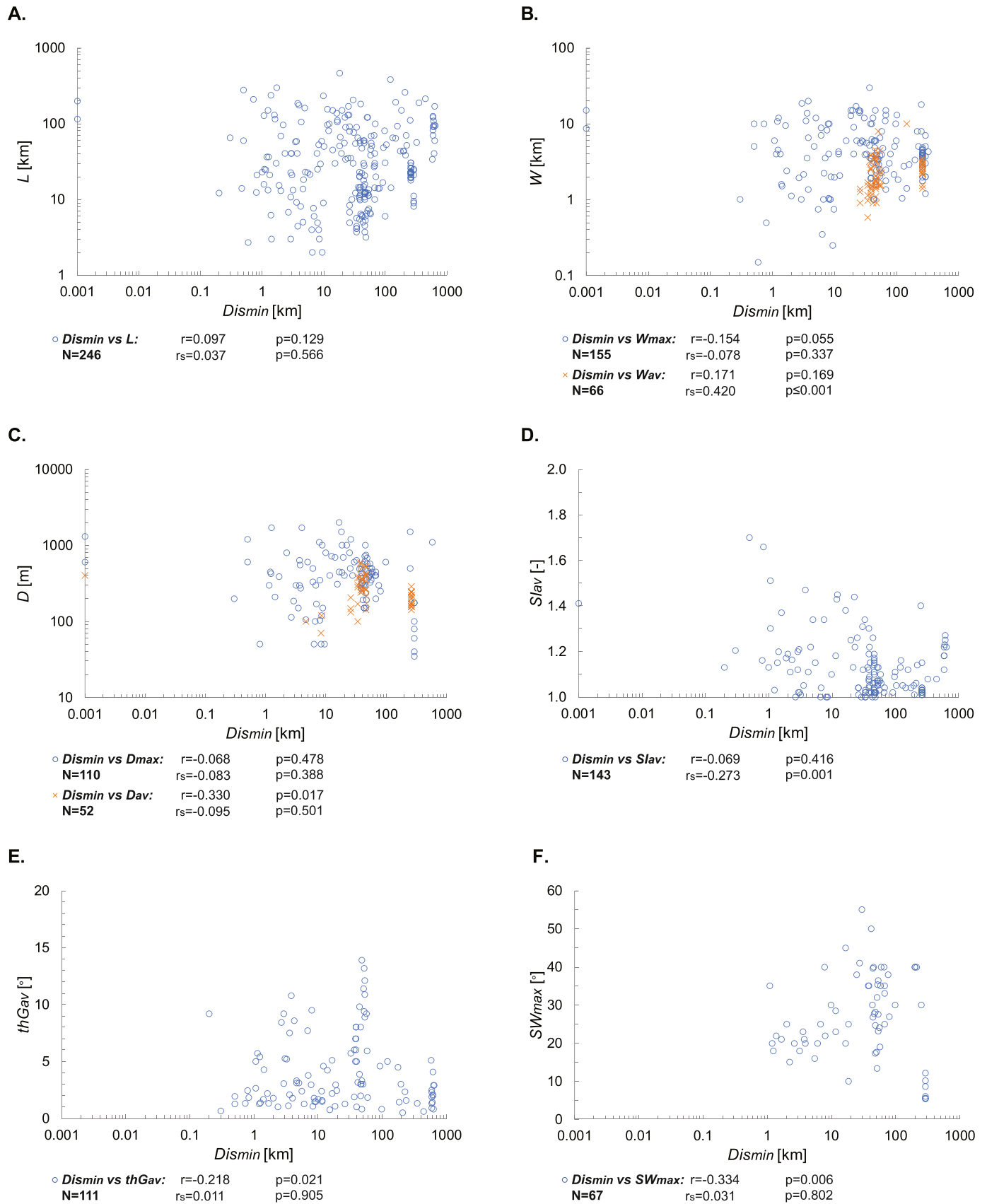


Fig. 6. a-f: Scatterplots of minimum canyon-shoreline distance and canyon morphometric parameters. N = number of observations; r = Pearson's correlation coefficient;  $r_s$  = Spearman's rank correlation coefficient. See Fig. 5 for key of abbreviations.

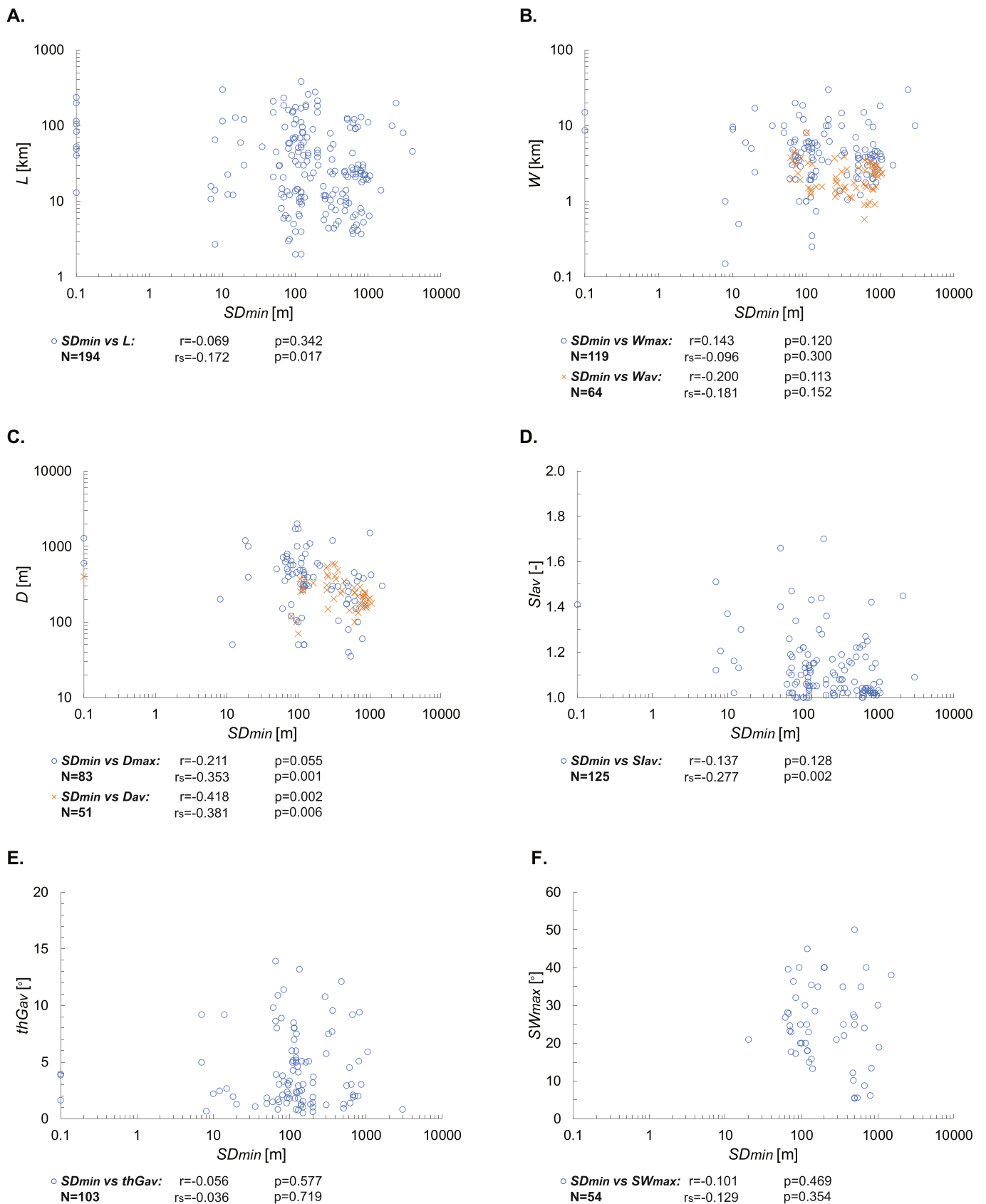
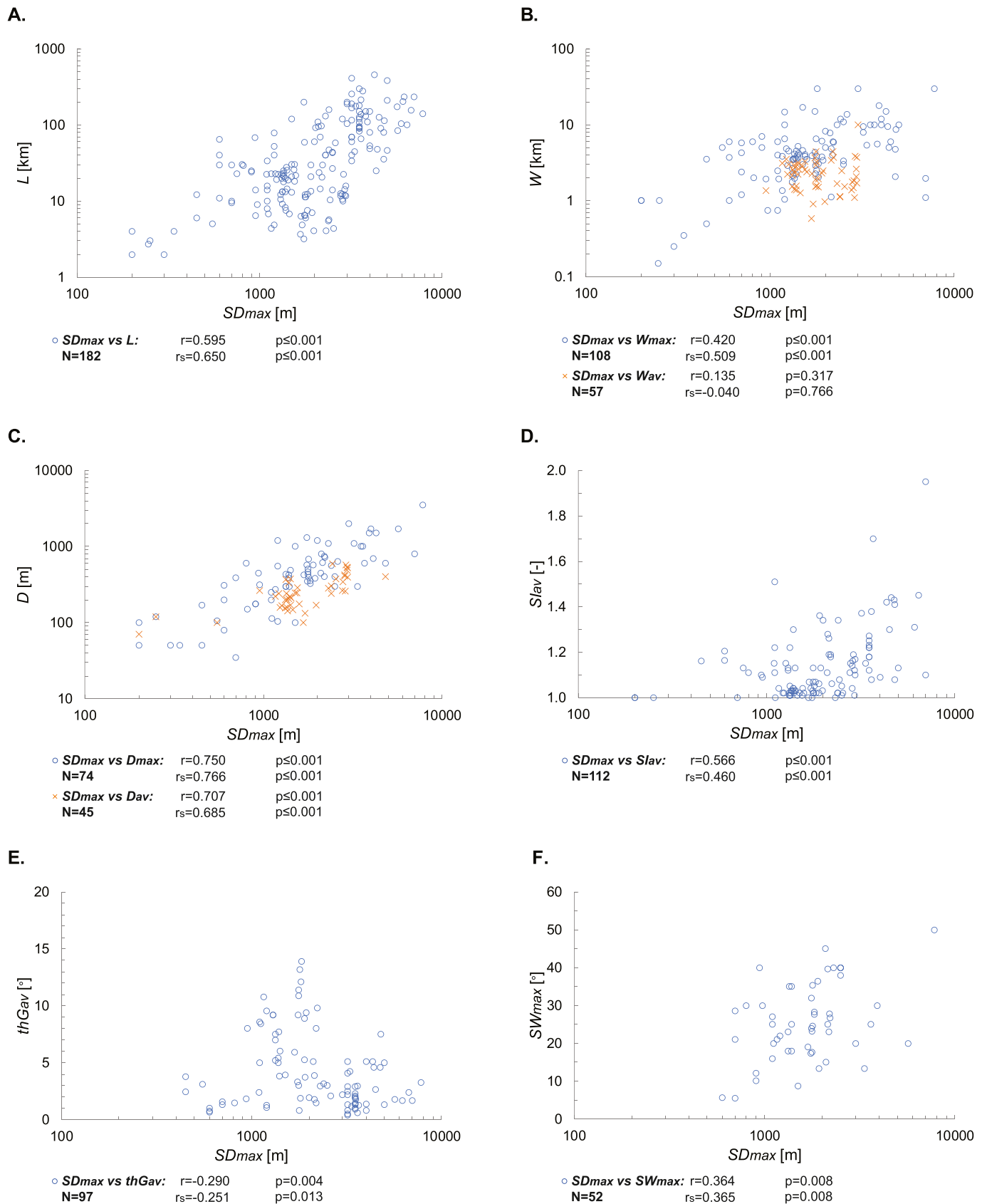


Fig. 7. a-f: Scatterplots of seafloor depth at the top of the canyon and canyon morphometric parameters. N = number of observations; r = Pearson's correlation coefficient;  $r_s$  = Spearman's rank correlation coefficient. See Fig. 5 for key of abbreviations.



**Fig. 8.** a-f: Scatterplots of seafloor depth at the canyon mouth and canyon morphometric parameters. N = number of observations; r = Pearson's correlation coefficient;  $r_s$  = Spearman's rank correlation coefficient. See Fig. 5 for key of abbreviations.

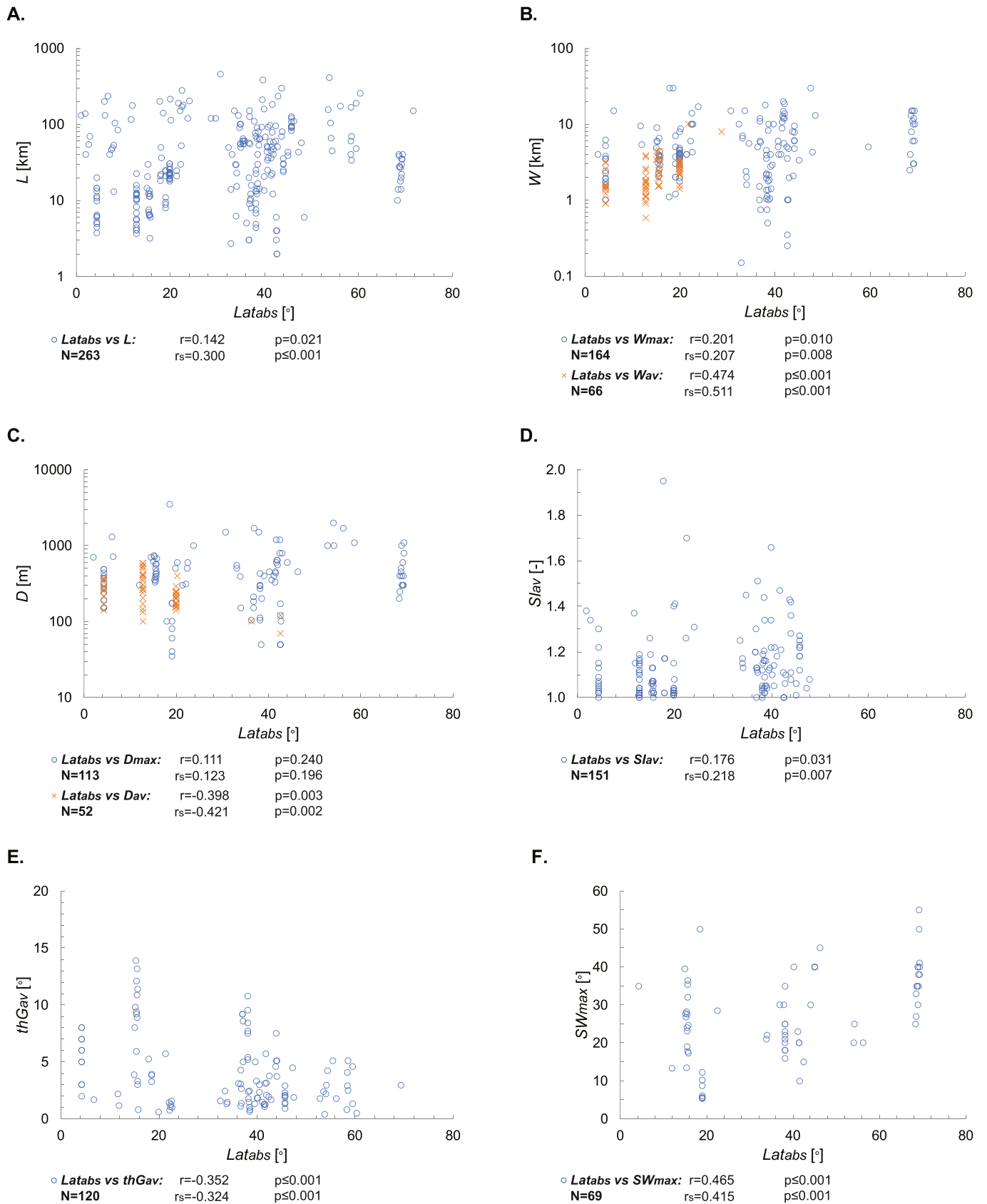


Fig. 9. a-f: Scatterplots of absolute values of latitude of the canyon apex and canyon morphometric parameters. N = number of observations; r = Pearson's correlation coefficient;  $r_s$  = Spearman's rank correlation coefficient. See Fig. 5 for key of abbreviations.

maximum canyon sidewall steepness (Fig. 9f). Weaker but statistically significant correlations are seen for canyon length (Fig. 9a), average canyon sinuosity (Fig. 9d) and the average canyon thalweg gradient (Fig. 9e), which are negative for the latter and positive for the first two variables.

### 5.3.2. Interpretations

The limited correlation between latitude and canyon morphometric parameters is interpreted to (i) arise from the complex ways in which climate can influence processes that can control canyon geomorphology (section 4.2); and (ii) reflect how the occurrence, frequency and magnitude of some processes vary with latitude, or are prevalent in – or even exclusive to – certain latitudinal belts.

Climate can variably influence sediment fluxes to marine environments and submarine canyons, for example by exerting controls on precipitation and subaerial erosion (e.g. Milliman and Farnsworth, 2011; Clift, 2020). Despite marked regional variations, annual precipitation rates decrease with latitude on a global scale (Milliman and Farnsworth, 2011). A general relationship between precipitation and denudation rates has been discussed in the literature (e.g. Fournier, 1949; Langbein and Schumm, 1958; Wilson, 1973; Milliman and Farnsworth, 2011; Zhang et al., 2022). Local and regional erosion rates might vary greatly due to the impact of additional factors such as lithology, tectonic uplift and vegetation cover (e.g. Kober et al., 2015; Torres Acosta et al., 2015; Starke et al., 2020). Hence, the weakness in correlation between latitude and canyon morphometrics might reflect the complex interrelationships between these factors, variability in the degree to which they are controlled by latitude, or that they are not important controls on submarine-canyon geomorphology.

Sediment discharge in rivers tends to peak during extreme weather events (e.g. Mulder and Syvitski, 1995), and to vary in concert with seasonal phenomena like monsoons (e.g. Clift, 2020). For example, cyclones can set the conditions that trigger hyperpycnal flows and turbidity currents at river mouths (e.g. Milliman and Kao, 2005). The passing of such cyclone-driven flows through submarine canyons is known from low-latitude regions including the South China Sea (e.g. Milliman and Kao, 2005; Zhang et al., 2018) and the Philippines (e.g. Sequeiros et al., 2019; Porcile et al., 2020), but cyclones also occur at temperate latitudes (e.g. Schultz et al., 2019; Son et al., 2022), and tend to preferentially occur in certain geographic regions in both hemispheres (e.g. Goni et al., 2009; Schultz et al., 2019). Storm-induced intra-canyon flows have been reported from many examples at tropical and temperate latitudes, and can also be linked to the remobilisation of shelf deposits as well as excess pore water pressure facilitating the remobilisation of surface sediments in the vicinity of canyon heads (e.g. Puig et al., 2004, 2014, and references therein).

Thus, climate-related factors that might exert control on canyon geomorphology are in many cases not tied to a certain latitudinal belt and cannot generally be captured by monotonic relationships across tropical and temperate zones.

The potential influence of glacial processes on canyon geomorphology is especially relevant to canyons in polar and mid-latitude regions that were covered by ice sheets during glacial intervals. Sediment can be supplied to slope environments by various glacial processes. The relative predominance of such processes and their importance as sediment sources to submarine canyons can vary over a glacial-interglacial cycle (e.g. Kagami et al., 1991; Gales et al., 2021; Ha et al., 2022). For example, during glacial and interglacial intervals, where ice sheets have prograded across continental shelves, sediment can be distributed to canyon heads via sediment gravity flows fed by subglacial ice streams and meltwater discharge (e.g. Kagami et al., 1991; Dowdeswell et al., 2004; Gales et al., 2021). In contrast, glacioisostatic shelf downwarping and uplift within the shelf might cause disconnection of canyons from sediment sources, by diverting sediment pathways and creating intrashelf sinks (e.g. Kagami et al., 1991). Moreover, ice-sheet loading along shelf margins during glacial maxima and sea-level

lowstands is considered a potential trigger to mass failures on continental slopes (e.g. Mulder and Moran, 1995; Gales et al., 2021). This mechanism might contribute to intra-canyon erosion by slope failures that would trigger, or evolve into, sediment gravity flows, and cause mass failures in canyons that have reached or retrograded into glaciated shelves. In addition, sediment can be supplied to slope systems from ice-rafted debris (e.g. Gales et al., 2021; Ha et al., 2022), a process which is influenced by climate but occurs during both glacial and interglacial periods (e.g. Hemming, 2004; Alvarez-Solas et al., 2013; Ha et al., 2022). Sediment can also be transported to canyons via down-canyon cascading of dense shelf water, as seen in the Antarctic Hillary Canyon (see Gales et al., 2021).

In high-latitude settings, sediment connection of canyons to terrestrial catchments might also be affected by glacial isostatic adjustment subsequent to glacial intervals leading to river diversions (e.g. Pico et al., 2018).

An example of steep canyon margins ( $>40^\circ$ ) is reported for submarine canyons along the Labrador margin (e.g. Dowdeswell et al., 2016). One factor that might contribute to steeper margins in canyons in higher latitudes is the glaciation of continental margins. The prevalence of line sources in glacial margin settings, as opposed to point sources in low-latitude settings, has been suggested (e.g. Martinsen, 2005; Armitage et al., 2010): sediment can be discharged rapidly from glaciers and ice streams, and distributed sediment dispersal across the continental slope (Martinsen, 2005) can promote the aggradation of canyon margins and inter-canyon ridges due to background sedimentation and overflow from channelised flows in canyons (e.g. Armitage et al., 2010; Gales et al., 2021), which in turn increase their proneness to slope failure (Armitage et al., 2010).

Although suitable data only include submarine canyons at latitudes up to  $45^\circ$ , the lack of any relationships between latitude and sinuosity is in agreement with findings by Harris and Whiteway (2011) for shelf-incising canyons (see their Fig. 9). The influence of latitude-related processes on submarine-channel sinuosity has been debated: an inverse relationship between channel sinuosity and latitude, linked to influence of the Coriolis force and variations in sediment type and flow type within different latitudinal zones, has been proposed (e.g. Peakall et al., 2012), but its robustness has been subsequently challenged (e.g. Sylvester and Pirmez, 2017). The results indicate that mechanisms invoked as latitudinal controls on sinuosity for submarine channels may not be applicable to submarine canyons. This research area needs further investigation.

Regardless, these considerations must be viewed with reservation due to the limited size of the datasets for arctic and tropical examples, and because of geographic bias. For example, canyons offshore NW Norway are accommodated on a passive margin in an open-sea setting, two environmental conditions that appear to promote steepening of canyon sidewalls; the former by promoting slope failure within canyons (section 7.2) and the latter by favouring canyon margin aggradation related to oceanic currents in open-sea settings (section 7.4).

## 6. Scaling relationships between canyon morphometric parameters and source-to-sink system attributes

Scaling relationships between canyon morphometric parameters and attributes of related terrestrial catchments, continental shelves and slopes have been evaluated. For 69 submarine canyons, which represent 24% of the studied canyons, scaling relationships between canyon and terrestrial-catchment parameters have been investigated, except for maximum canyon sidewall steepness, average canyon width and depth, due to data paucity. The same applies for correlations of average canyon width and depth with slope characteristics.

An overview of the results is presented in form of heatmaps of correlation (Fig. 10a-c). Furthermore, relationships between attributes of canyon-associated S2S systems (Fig. 11) have been investigated. This has been undertaken to aid in the interpretation of controls on canyon

**A. Terrestrial catchment**

**Pearson's correlation coefficient r**

L	0.184	0.244	0.210	0.387
W <sub>max</sub>	0.358	0.306	0.452	0.633
D <sub>max</sub>	0.414	***	0.372	***
SI <sub>av</sub>	-0.075	0.057	-0.089	0.586
thG <sub>av</sub>	-0.345	***	-0.273	-0.193
SW <sub>max</sub>	***	***	***	***
	L fls	Q fls	A flsc	H flsc

**Spearman's rank correlation coefficient rs**

L	0.107	0.666	0.137	0.636
W <sub>max</sub>	0.424	0.123	0.633	0.588
D <sub>max</sub>	0.736	***	0.737	***
SI <sub>av</sub>	-0.165	0.510	-0.127	0.602
thG <sub>av</sub>	-0.171	***	-0.106	-0.286
SW <sub>max</sub>	***	***	***	***
	L fls	Q fls	A flsc	H flsc

**p-value**

L	0.130	0.091	0.091	0.003
W <sub>max</sub>	0.056	0.232	0.014	0.001
D <sub>max</sub>	0.098	***	0.117	***
SI <sub>av</sub>	0.601	0.743	0.539	≤0.001
thG <sub>av</sub>	0.067	***	0.138	0.402
SW <sub>max</sub>	***	***	***	***
	L fls	Q fls	A flsc	H flsc

**p-value**

L	0.381	≤0.001	0.274	≤0.001
W <sub>max</sub>	0.022	0.639	≤0.001	0.002
D <sub>max</sub>	0.001	***	≤0.001	***
SI <sub>av</sub>	0.248	0.002	0.378	≤0.001
thG <sub>av</sub>	0.375	***	0.572	0.208
SW <sub>max</sub>	***	***	***	***
	L fls	Q fls	A flsc	H flsc

**Fig. 10.** a-c: Heat maps for correlations of canyon morphometrics with variables of the associated source-to-sink system displaying values of Pearson's correlation coefficient r and Spearman's rank correlation coefficient rs, and their respective p-values. A. Terrestrial catchment. B. Continental shelf. C. Continental slope. L = canyon length; W<sub>max</sub> = maximum canyon width; W<sub>av</sub> = average canyon width; D<sub>max</sub> = maximum canyon depth; D<sub>av</sub> = average canyon depth; SI<sub>av</sub> = average canyon sinuosity index; thG<sub>av</sub> = average canyon thalweg gradient; SW<sub>max</sub> = maximum canyon sidewall steepness; L<sub>fls</sub> = fluvial system length; Q<sub>fls</sub> = average annual fluvial discharge; A<sub>flsc</sub> = size of the catchment; H<sub>flsc</sub> = maximum elevation in the catchment area; W<sub>sh</sub> = shelf width; D<sub>sh</sub> = shelf-break depth; G<sub>sh</sub> = average shelf gradient; W<sub>sl</sub> = slope width; D<sub>sl</sub> = slope-break depth; G<sub>sl</sub> = average slope gradient; \*\*\* indicates scarcity of data (N<15).

**B. Continental shelf**

**Pearson's correlation coefficient r**

L	0.223	0.382	-0.162
W <sub>max</sub>	0.071	0.362	-0.133
W <sub>av</sub>	0.189	0.496	0.692
D <sub>max</sub>	0.213	0.362	-0.208
D <sub>av</sub>	-0.346	***	-0.384
SI <sub>av</sub>	-0.042	0.387	0.249
thG <sub>av</sub>	-0.244	-0.348	-0.095
SW <sub>max</sub>	0.552	-0.152	-0.395
	W sh	D sh	G sh

**Spearman's rank correlation coefficient rs**

L	0.238	0.537	-0.188
W <sub>max</sub>	0.164	0.270	-0.028
W <sub>av</sub>	0.398	0.555	0.592
D <sub>max</sub>	0.411	0.217	-0.239
D <sub>av</sub>	-0.227	***	-0.353
SI <sub>av</sub>	-0.252	0.437	0.150
thG <sub>av</sub>	-0.155	-0.334	0.005
SW <sub>max</sub>	0.457	-0.051	-0.408
	W sh	D sh	G sh

**p-value**

L	0.002	≤0.001	0.082
W <sub>max</sub>	0.440	0.002	0.280
W <sub>av</sub>	0.128	0.009	≤0.001
D <sub>max</sub>	0.061	0.004	0.110
D <sub>av</sub>	0.012	***	0.157
SI <sub>av</sub>	0.620	0.001	0.035
thG <sub>av</sub>	0.012	0.002	0.404
SW <sub>max</sub>	≤0.001	0.439	0.038
	W sh	D sh	G sh

**p-value**

L	0.001	≤0.001	0.043
W <sub>max</sub>	0.076	0.025	0.823
W <sub>av</sub>	0.001	0.003	0.001
D <sub>max</sub>	≤0.001	0.096	0.066
D <sub>av</sub>	0.105	***	0.197
SI <sub>av</sub>	0.002	≤0.001	0.207
thG <sub>av</sub>	0.116	0.003	0.962
SW <sub>max</sub>	0.003	0.797	0.031
	W sh	D sh	G sh

**C. Continental slope**

**Pearson's correlation coefficient r**

L	0.439	0.207	-0.099
W <sub>max</sub>	0.407	0.145	-0.125
W <sub>av</sub>	***	***	***
D <sub>max</sub>	0.442	0.601	-0.023
D <sub>av</sub>	***	***	***
SI <sub>av</sub>	0.121	0.231	-0.316
thG <sub>av</sub>	-0.416	-0.002	0.493
SW <sub>max</sub>	-0.427	-0.150	0.758
	W sl	D sl	G sl

**Spearman's rank correlation coefficient rs**

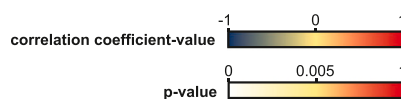
L	0.875	0.371	-0.246
W <sub>max</sub>	0.700	0.032	-0.141
W <sub>av</sub>	***	***	***
D <sub>max</sub>	0.637	0.462	0.112
D <sub>av</sub>	***	***	***
SI <sub>av</sub>	-0.234	0.208	-0.383
thG <sub>av</sub>	-0.504	0.062	0.461
SW <sub>max</sub>	-0.286	-0.628	0.744
	W sl	D sl	G sl

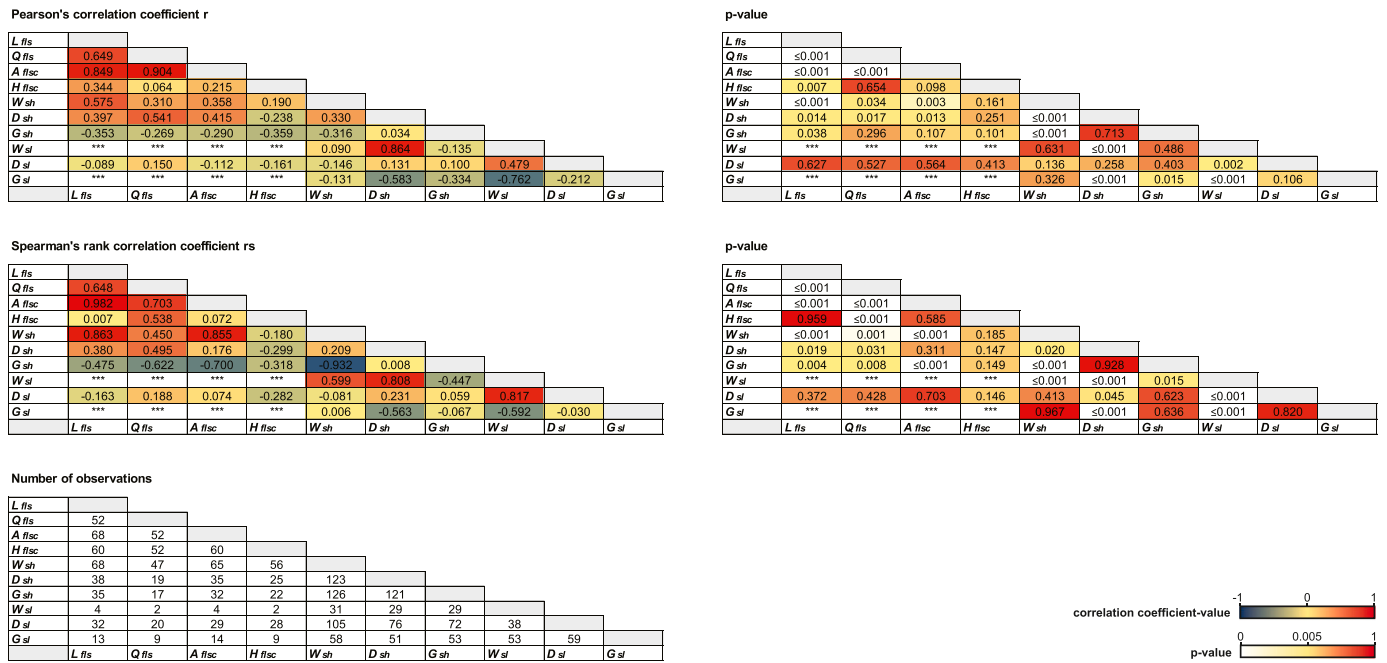
**p-value**

L	0.001	0.014	0.370
W <sub>max</sub>	0.008	0.179	0.340
W <sub>av</sub>	***	***	***
D <sub>max</sub>	0.003	≤0.001	0.868
D <sub>av</sub>	***	***	***
SI <sub>av</sub>	0.655	0.076	0.053
thG <sub>av</sub>	0.020	0.983	≤0.001
SW <sub>max</sub>	0.060	0.367	≤0.001
	W sl	D sl	G sl

**p-value**

L	≤0.001	≤0.001	0.023
W <sub>max</sub>	≤0.001	0.772	0.284
W <sub>av</sub>	***	***	***
D <sub>max</sub>	≤0.001	≤0.001	0.417
D <sub>av</sub>	***	***	***
SI <sub>av</sub>	0.383	0.111	0.018
thG <sub>av</sub>	0.004	0.597	≤0.001
SW <sub>max</sub>	0.221	≤0.001	≤0.001
	W sl	D sl	G sl





**Fig. 11.** Heat maps for correlations of variables of the source-to-sink system specific to studied canyons displaying values of Pearson's correlation coefficient  $r$  and Spearman's rank correlation coefficient  $r_s$ , and their respective  $p$ -values.  $L_{fls}$  = fluvial system length;  $Q_{fls}$  = average annual fluvial discharge;  $A_{fisc}$  = size of the catchment;  $H_{fisc}$  = maximum elevation in the catchment area;  $W_{sh}$  = shelf width;  $D_{sh}$  = shelf-break depth;  $G_{sh}$  = average shelf gradient;  $W_{sl}$  = slope width;  $D_{sl}$  = slope-break depth;  $G_{sl}$  = average slope gradient; \*\*\* indicates scarcity of data ( $N < 15$ ).

morphometry by identifying where relationships might in part reflect covariance with one or several other factors. Correlations of canyon morphometrics with attributes of the catchment, shelf and slope are presented as scatterplots in sections 6.1 to 6.3 (Figs. 12–15), in which the findings for the individual S2S segments are discussed. In addition, canyon morphometry has been quantitatively assessed for canyons grouped based on shelf-break thresholds of 120 m and 130 m below present-day sea level at the site of the canyon (Fig. 14a-f).

6.1. Terrestrial catchment

6.1.1. Observations

Fluvial system length displays moderate and statistically significant positive correlation with maximum canyon depth (Fig. 12i), and modest but not significant positive correlation with maximum canyon width (Fig. 12e).

Similarly, moderate significant positive correlations between catchment size and canyon maximum depth and width are seen (Figs. 12 g&k).

Average annual fluvial discharge has moderate direct correlations with canyon length (Fig. 12b) and average canyon sinuosity (Fig. 12n); both relationships are statistically significant.

Moderate statistically significant positive correlations exist between maximum catchment elevation and canyon length (Fig. 12d), maximum width (Fig. 12h) and average sinuosity (Fig. 12p).

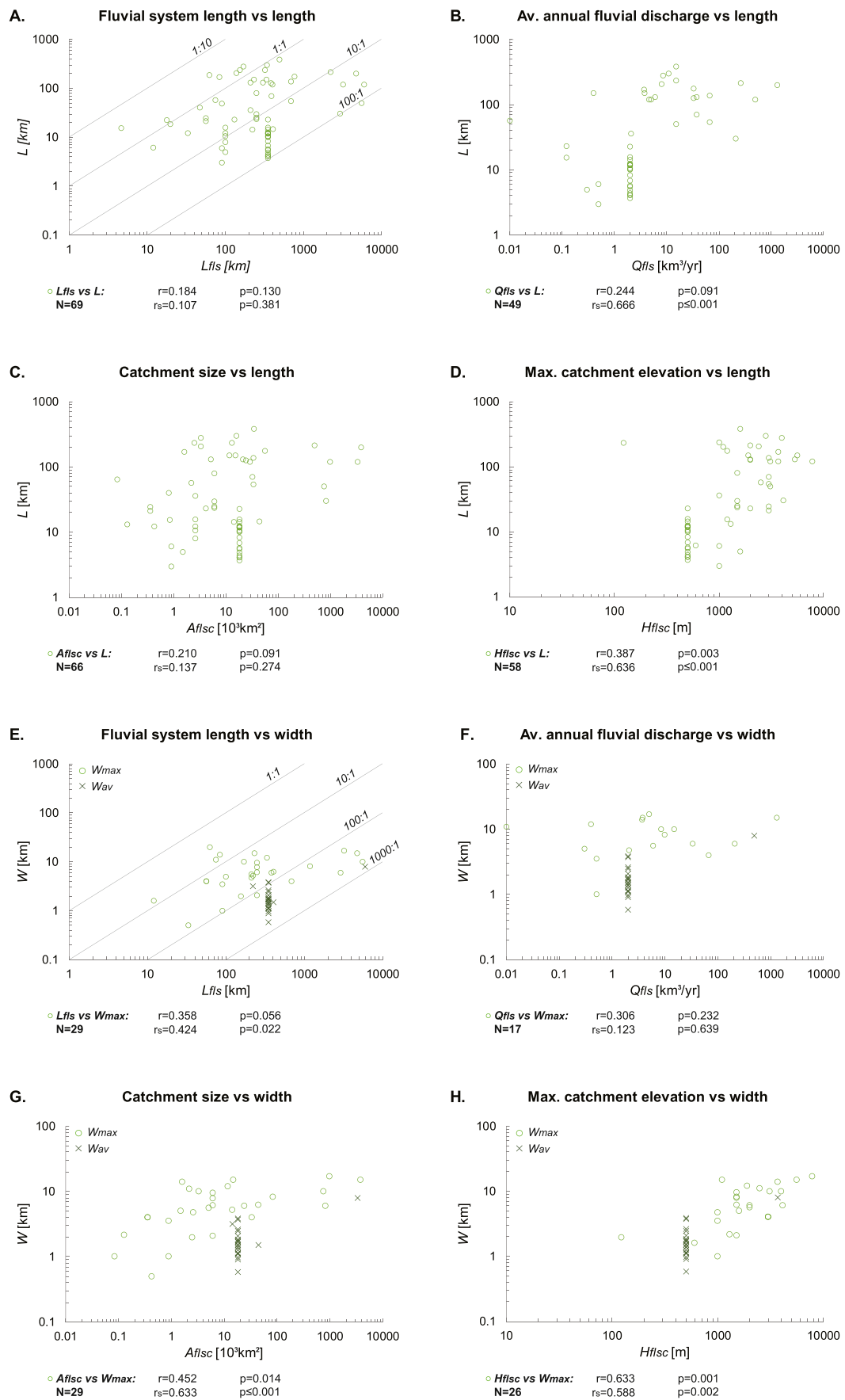
6.1.2. Interpretations

The observed relationships between canyon length, maximum canyon depth and average canyon sinuosity with attributes of the terrestrial catchment likely reflect how fluvial sediment discharge can promote intra-canyon erosion by down-canyon flows, e.g. the upslope lengthening of canyons at their apices (e.g. Piper and Normark, 2009), their deepening in the region of canyon mouths, and how the streamwise length of more sinuous canyons is inherently longer (see section 5.2.2.2).

The extent to which the morphology of a submarine canyon is

affected by fluvial sediment discharge depends on its erosional versus depositional impact on individual canyon morphometrics, which is determined by many factors and their interplay. The bedrock lithology of terrestrial source areas has been invoked as a control on canyon formation in view of how it can influence the runout distance and erosive strength of submarine flows, e.g. by affecting sediment density, composition and transport mechanisms (Smith et al., 2017). In addition, characteristics of the seafloor substrate can impact its erodibility, which also has an effect on the magnitude of intra-canyon erosion by the flows; for example carbonate cementation can decrease erodibility and stabilise the substrate and canyon walls (e.g. Oiwane et al., 2011), thereby reducing the potential of mass failure on slopes (e.g. Chang et al., 2021) and within canyons. With increasing distance between the river mouth and the submarine canyon head, the sediment transport efficiency decreases as a function of distance and grain size. A global study on sediment delivery to submarine canyons from fluvial systems (Sweet and Blum, 2016) indicates that canyons tend to intercept gravel-sized sediment when their head is within ca. 500 m of a fluvial source, sand-sized sediment when it is within 1 to 5 km, and silt and clay-sized sediment when it is within ca. 40 km. The segregation of grain sizes in shelf-crossing submarine flows can impact canyon evolution; findings from studies of the Monterey Canyon suggest that the presence of unconsolidated sands within a canyon might be a prerequisite for intra-canyon turbidity current generation (Paull et al., 2018), whereas surficial mud deposits on the canyon floor might promote self-acceleration of these flows (Hereema et al., 2020).

The variability of these factors across S2S systems can explain the weakness with which canyon morphometric parameters are scaled with attributes of the terrestrial catchments. Weakness in correlation may also be due to other controls overprinting the effect of fluvial discharge on canyon geomorphology; these controls may include, for example, intra-canyon sedimentary processes (see section 4.2.1), hydrodynamic processes (section 4.2.2), structural controls (section 4.2.3) and biogenic processes (section 4.2.4), as well as sediment remobilisation within the shelf and slope.



**Fig. 12.** a-t: Scatterplots between attributes of terrestrial catchments and canyon morphometric parameters. N = number of observations; r = Pearson's correlation coefficient;  $r_s$  = Spearman's rank correlation coefficient. See [Tab. 2](#) for key of abbreviations.



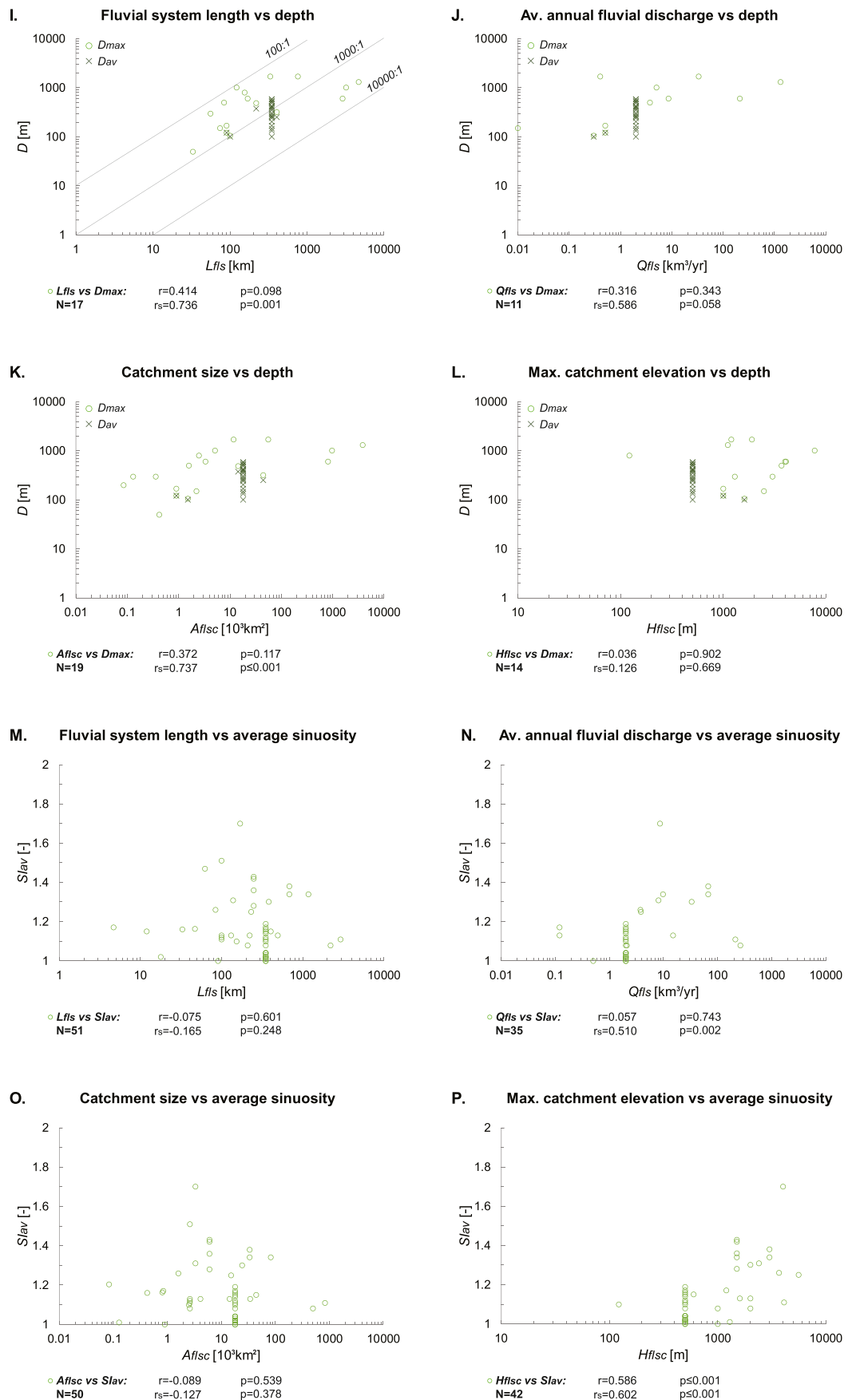


Fig. 12. (continued).

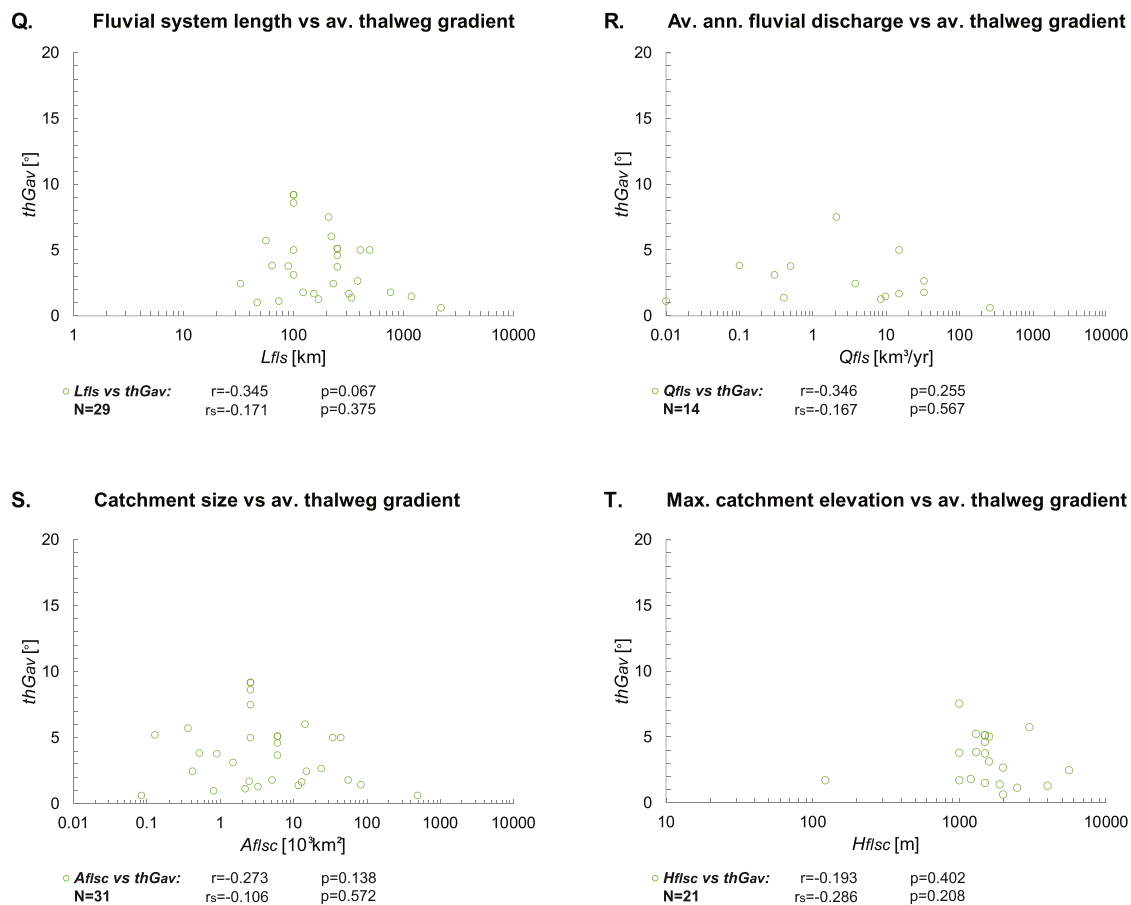


Fig. 12. (continued).

## 6.2. Continental shelf

### 6.2.1. Observations

The shelf width is moderately directly correlated with the maximum canyon sidewall steepness (Fig. 13p), and only modestly with average canyon width (Fig. 13d) and maximum canyon depth (Fig. 13g). The shelf width is directly correlated with the canyon length (Fig. 13a) and inversely with the average canyon sinuosity (Fig. 13j), but these relationships are weak.

The shelf-break depth correlates significantly with all investigated canyon morphometric parameters except for the maximum canyon sidewall steepness (Fig. 13q), exhibiting moderate positive correlation with the canyon length (Fig. 13b) and modest correlation with the average canyon sinuosity (Fig. 13k); correlations with maximum width (Fig. 13e) and depth (Fig. 13h) are weaker. In contrast, the average canyon thalweg gradient shows weak but significant inverse scaling with the shelf-break depth (Fig. 13n). Moderate scaling exists between the shelf-break depth and the average canyon width, but the data stem from two geographic regions only: offshore NE Australia and NE Brazil, both associated with shallow (70–85 m) shelves (Fig. 13e).

Correlations of canyon morphometric parameters with the average shelf gradient are mostly weak and not significant (Fig. 13a–r). Moderate and significant correlation is observed between shelf gradient and average canyon width (Fig. 13f), but these results are based on data from two geographic regions only. Modest inverse correlation is seen between shelf gradient and maximum canyon sidewall steepness, which is not statistically significant (Fig. 13r).

Submarine canyons with a present-day shelf break deeper than 120 m bsl are on average longer and have greater maximum widths and depths, higher average canyon sinuosities and lower average canyon thalweg

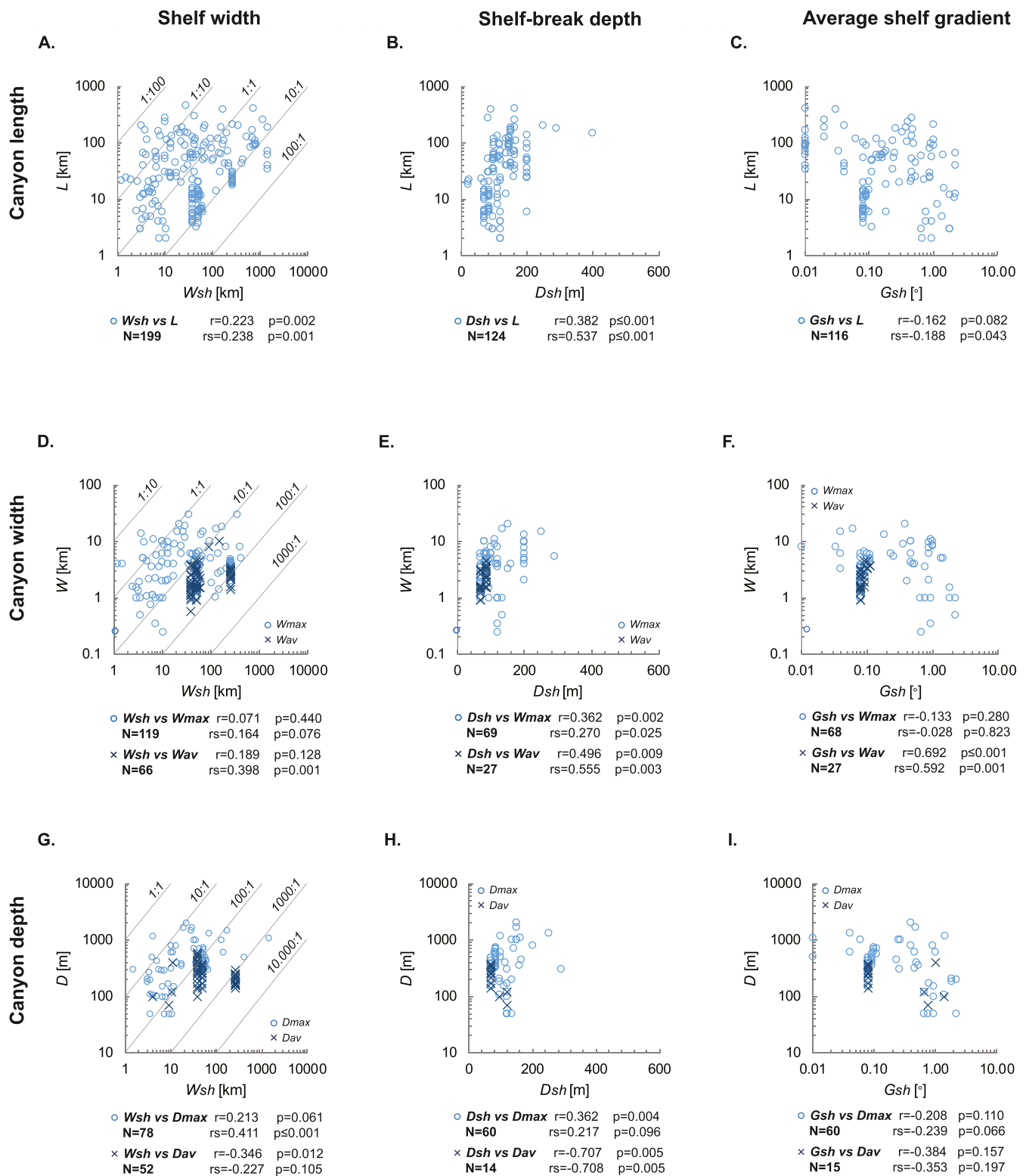
gradients than canyons with a shelf-break shallower than 120 m bsl. The same trends are seen for groups of canyons distinguished based on a threshold of shelf-break depth of 130 m (Fig. 14a–f). Although a greater range in maximum canyon sidewall steepness is seen in canyons associated with shelf breaks deeper than 120 m, average values between both canyon groups are very similar. Data on maximum canyon depth and maximum canyon sidewall steepness that can be employed in this analysis are limited, whereas data on average width and depth are only available for canyons installed on slopes with shelf breaks shallower than 120 m.

### 6.2.2. Interpretations

The width of the shelf plays a role in across-shelf sediment distribution from fluvial outlets to the shelf edge (e.g. Sweet et al., 2020). Narrower shelves are characterised by shorter distances to fluvial outlets that can deliver sediment to canyon heads, and may allow sediment connection of canyons with rivers and littoral cells to be maintained during sea-level highstands (e.g. Covault et al., 2007; Normark et al., 2009; Jipa and Panin, 2020). Steeper shelf gradients might also inhibit deposition by hyperpycnal flows and promote bedload transport of coarse sediment from rivers across shelves (e.g. Jipa and Panin, 2020).

By contrast, the effect of hydroisostasy on continental levering and the ensuing steepening of continental shelves is thought to be stronger for wider shelves, probably by a factor  $\leq 0.3$  since the Last Glacial Maximum (LGM), relative to narrower shelves (Hutton et al., 2013). Nevertheless, despite being more prone to hydroisostatic flexure, wider shelves tend to have gentler gradients than narrower shelves.

Wider shelves also tend to have resulted from greater shelf-edge progradation, which can occur in response to greater rates of sediment supply to the outer shelf and upper slope from terrestrial catchments and from shelf-internal sources (e.g. Mougenot et al., 1983; Carvajal et al., 2009;



**Fig. 13.** a-r: Scatterplots between attributes of the continental shelf and canyon morphometric parameters. N = number of observations; r = Pearson's correlation coefficient;  $r_s$  = Spearman's rank correlation coefficient. See Tab. 2 for key of abbreviations.

Blum et al., 2013), as well as from the up-building of slope sediment prisms from drifts (e.g. Fulthorpe and Carter, 1991). However, although a wider shelf indicates a more sustained sediment supply to a shelf margin, sediment transport across wide shelves into submarine canyons is most

effective for canyons that have significantly retrograded the shelf and/or are connected with a river, either directly or via shelf channels or shelf-edge deltas. With increasing shelf width, the effectiveness of across-shelf sediment transport from fluvial outlets decreases for coarser grained

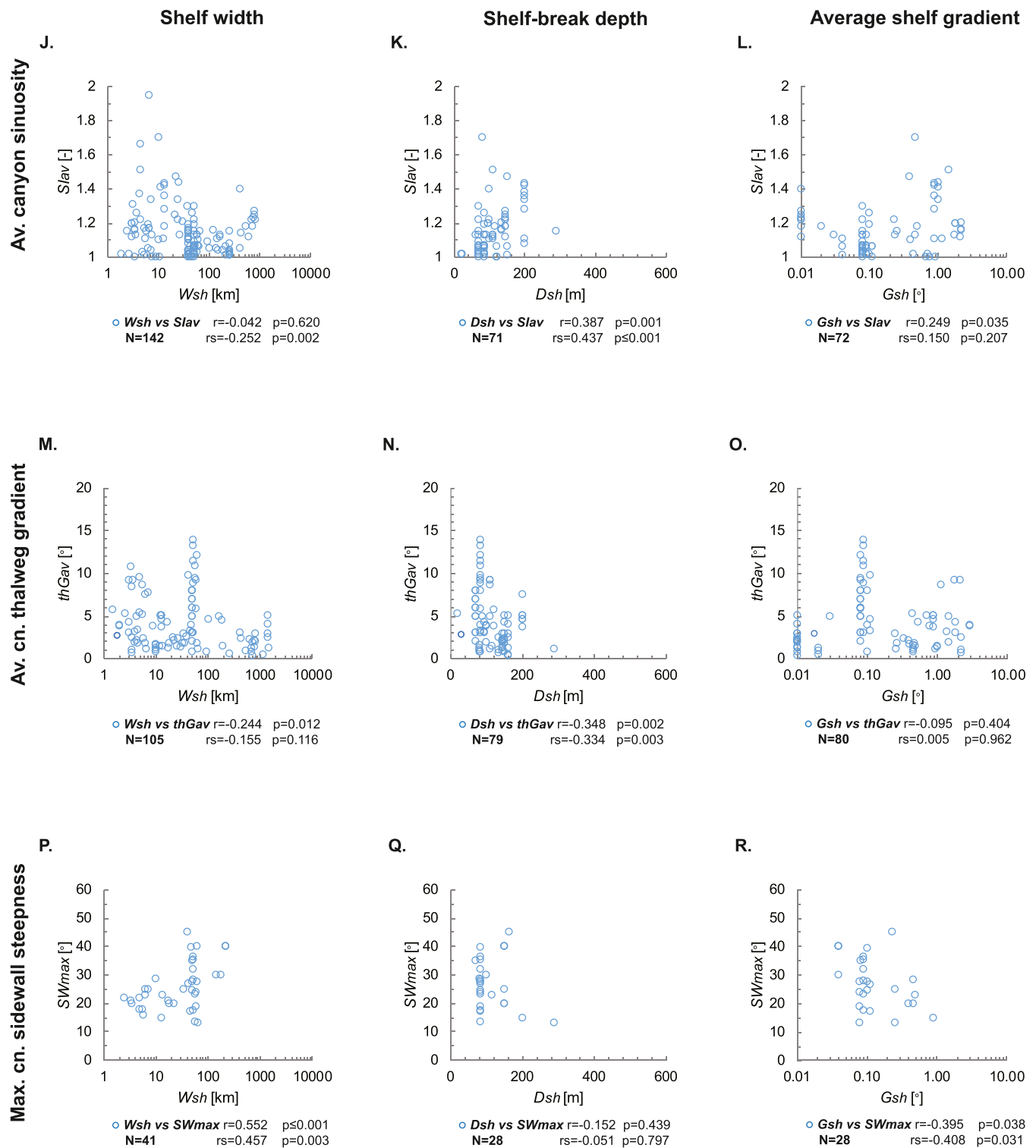


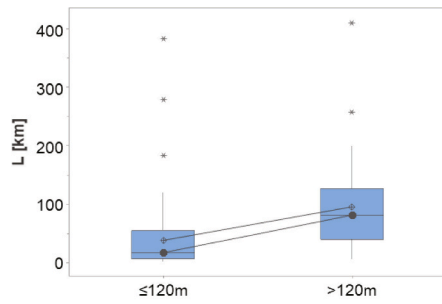
Fig. 13. (continued).

sediment, leading to variations in grain-size distribution of sediment discharged from rivers across the shelf. Hence, the importance of erosion by submarine flows linked to rivers on canyon morphology becomes likely less significant on shelves wider than 5 km, given the expected paucity of sand grain-size fractions reaching beyond this boundary (section 6.1). In addition, the frequency and magnitude of hyperpycnal flows can be affected by factors other than the shelf width, such as salinity of the water body, climate and relative sea-level change (e.g. Mulder et al., 2003; Dadson

et al., 2005).

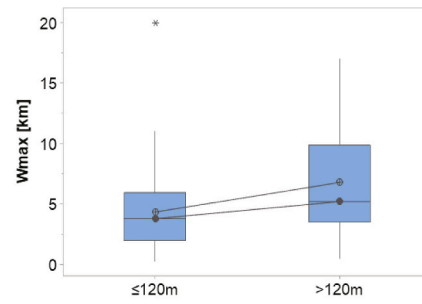
The effectiveness of across-shelf sediment transport is also affected by hydrodynamic processes associated with tidal currents, along-shelf currents and waves (Nittrouer and Wright, 1994; Wang et al., 2010). The ability of waves to remobilise sediment is greater at shallower depths (Peters and Loss, 2012); this sediment transport mechanism might have a greater areal effect on wide and shallow shelves with lower gradients.

**A. Length**



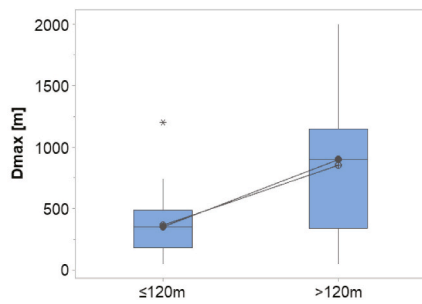
	N	min	mean	StDev	median	max
≤120	78	2.00	38.14	58.60	17.02	384.05
>120	46	6.00	95.50	74.00	81.30	411.00
<b>T-Value = -7.48 DF = 119 P-Value ≤ 0.001</b>						
≤130	78	2.00	37.45	57.15	17.02	384.05
>130	46	6.00	96.60	75.00	81.30	411.00
<b>T-Value = -7.55 DF = 119 P-Value ≤ 0.001</b>						

**B. Maximum width**



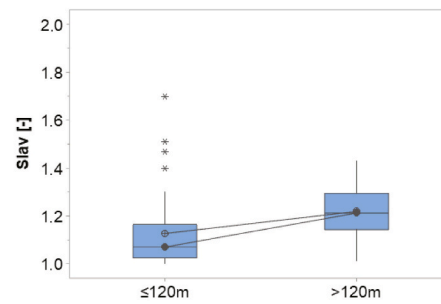
	N	min	mean	StDev	median	max
≤120	53	0.25	4.33	3.37	3.78	20.00
>120	16	0.50	6.79	4.91	5.20	17.00
<b>T-Value = -1.56 DF = 22 P-Value = 0.134</b>						
≤130	52	0.25	4.03	2.58	3.78	11.00
>130	17	0.50	7.56	5.73	5.40	20.00
<b>T-Value = -2.46 DF = 18 P-Value = 0.024</b>						

**C. Maximum depth**



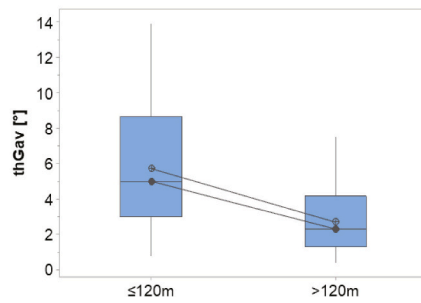
	N	min	mean	StDev	median	max
≤120	46	50.00	364.50	225.50	350.00	1200.00
>120	14	50.00	854.00	567.00	900.00	2000.00
<b>T-Value = -3.15 DF = 14 P-Value = 0.007</b>						
≤130	46	50.00	364.50	225.50	350.00	1200.00
>130	14	50.00	854.00	567.00	900.00	2000.00
<b>T-Value = -3.15 DF = 14 P-Value = 0.007</b>						

**D. Average canyon sinuosity**



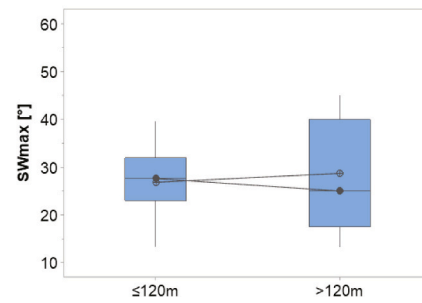
	N	min	mean	StDev	median	max
≤120	49	1.00	1.13	0.14	1.07	1.70
>120	22	1.01	1.22	0.12	1.21	1.43
<b>T-Value = -3.15 DF = 48 P-Value = 0.003</b>						
≤130	48	1.00	1.12	0.14	1.07	1.70
>130	23	1.01	1.23	0.12	1.22	1.47
<b>T-Value = -3.66 DF = 46 P-Value = 0.001</b>						

**E. Average canyon thalweg gradient**



	N	min	mean	StDev	median	max
≤120	46	0.78	5.72	3.53	5.00	13.90
>120	33	0.40	2.69	1.72	2.30	7.50
<b>T-Value = 5.04 DF = 69 P-Value ≤ 0.001</b>						
≤130	46	0.78	5.72	3.53	5.00	13.90
>130	33	0.40	2.69	1.72	2.30	7.50
<b>T-Value = 5.04 DF = 69 P-Value ≤ 0.001</b>						

**F. Maximum canyon sidewall steepness**



	N	min	mean	StDev	median	max
≤120	19	13.40	26.82	7.05	27.60	39.60
>120	9	13.30	28.70	12.44	35.00	45.00
<b>T-Value = -0.42 DF = 10 P-Value = 0.681</b>						
≤130	19	13.40	26.82	7.05	27.60	39.60
>130	9	13.30	28.70	12.44	35.00	45.00
<b>T-Value = -0.42 DF = 10 P-Value = 0.681</b>						

**Fig. 14.** a-f: Boxplots of frequency distributions of canyon morphometric parameters for studied canyons distinguished based on shelf-break depth thresholds of 120 m at the canyon. Tabulated statistics refer to canyon grouped based on shelf-break thresholds of 120 m and 130 m bsl, respectively. N = number of readings; min = minimum value; mean = mean value; StDev = standard deviation; median = median value; max = maximum value. See Tab. 2 for key of abbreviations.

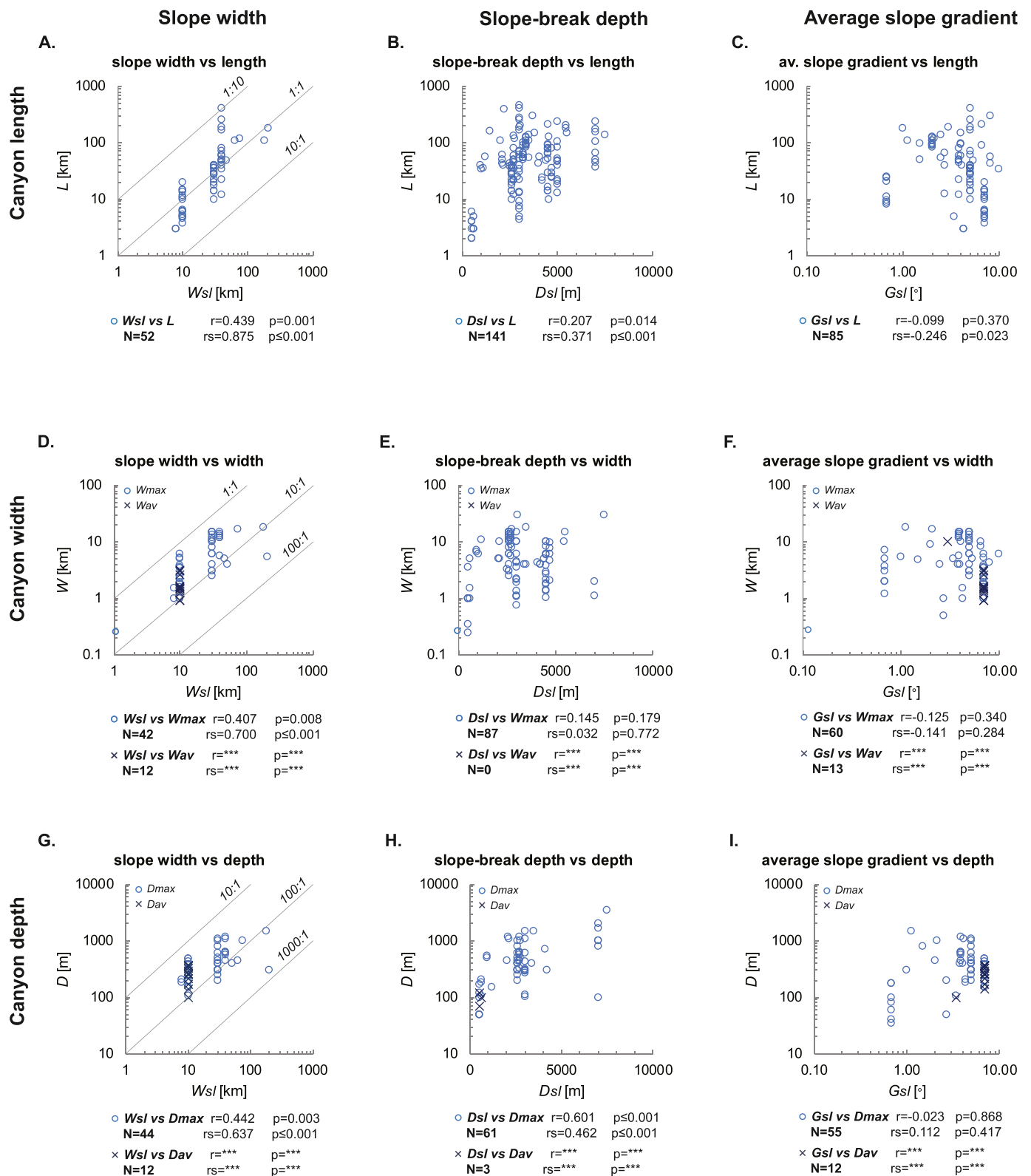


Fig. 15. a-r: Scatterplots between attributes of the slope vs canyon morphometrics.  $N$  = number of observations;  $r$  = Pearson's correlation coefficient;  $rs$  = Spearman's rank correlation coefficient. See Tab. 2 for key of abbreviations.

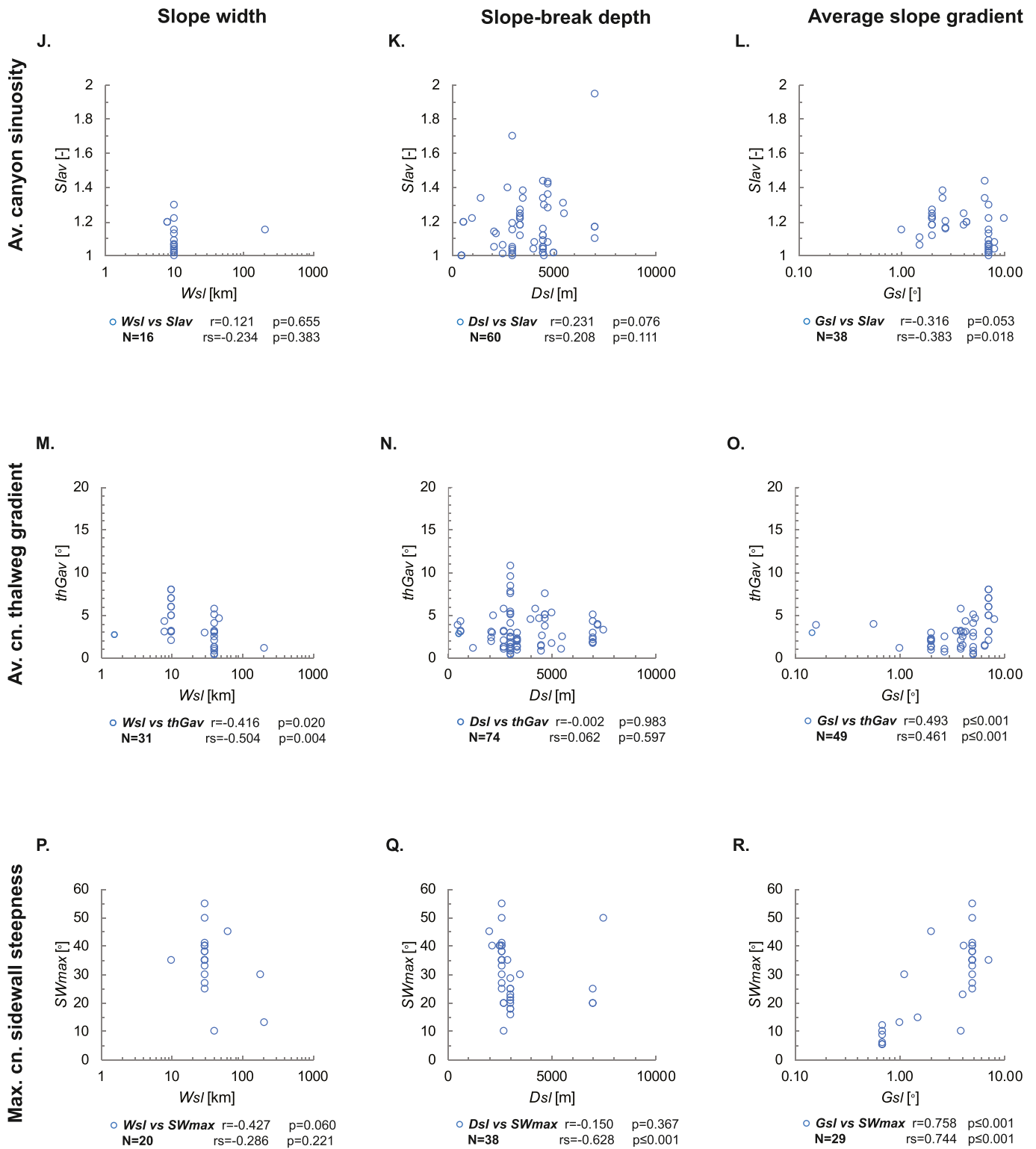


Fig. 15. (continued).

Moreover, the shelf topography can variably affect across-shelf sediment dispersal into submarine canyons: shelf uplift and deformation by tectonic activity (e.g. Johnson et al., 2017) and the presence of reefs (see section 4.2.3) can create seafloor topography and modify shelf gradients, which in turn can force sediment transport pathways through shelf valleys and submarine canyons incising the shelf. Currents, waves and flows carrying sediment might also be deflected away from canyons

by intrashelf highs of variable origin.

The subaerial exposure of continental shelves at lowstand can lead to the amalgamation of river catchment areas as confluences are established; this might significantly enhance sediment supply to individual fluvial outlets, and in turn to canyons with sediment connectivity to these systems, especially for large fluvial systems that can arise as wide shelves are exposed (Blum et al., 2013). Additional sediment might be

conveyed to canyons from the local erosion of shelf substrate when rivers traverse the exposed shelf (e.g. Sweet et al., 2020).

Some of the scaling relationships between shelf configuration and canyon morphometrics may also be due to covariance with other related parameters. For example, scaling of canyon length with shelf-break depth might in part reflect how deeper shelves are associated with wider slopes, and how shelf-break depths tend to increase for terrestrial catchments associated with larger fluvial systems or multiple fluvial sources, greater average annual discharge and catchment size. However, scaling relationships between shelf-break depth and attributes of the terrestrial catchment are not significant.

During episodes of sea-level lowstand, such as during the LGM, canyons with their heads in vicinity of the shelf-edge could be fed by fluvial systems that had prograded onto the shelves (e.g. Sweet et al., 2020).

In sequence stratigraphic models, routing of significant volumes of sand-sized sediment across continental slopes to basin floors and the development of submarine fans is perceived to be most effective during relative sea-level lowstands (e.g. Posamentier et al., 1991), which would suggest that canyon evolution by down-canyon sediment gravity flows might also be enhanced during these intervals. Reconstructions and estimates for the eustatic fall during the LGM have been variably placed between ca. 120 m to 135 m bsl (e.g. Clark and Mix, 2002; Simms et al., 2019, and references therein), so that most shelves with shelf breaks shallower than 120 m bsl have likely been subaerially exposed during the LGM. Despite this, the studied canyons hosted on shelves with shelf breaks deeper than 120 m bsl tend to be larger, to be more sinuous, and to have lower canyon thalweg gradients than those with shelf breaks at 120 m or less. This indicates that sediment connection of canyons to rivers and littoral cells during phases of sea-level lowstands is not as important a control on canyon geomorphology compared to other controls. The findings might also indicate how deeper shelves tend to be associated with larger terrestrial catchments (Fig. 15; Wang et al., 2019).

The complex role of shelf physiography and across-shelf sediment transport, together with covariance in shelf and canyon characteristics in response to common controls on sediment dispersal, explain the limited value of shelf configuration as a predictor of canyon geomorphology.

### 6.3. Continental slope

#### 6.3.1. Observations

The slope width exhibits strong and significant correlation with canyon length (Fig. 15a), and moderate significant correlations with maximum width (Fig. 15d), maximum depth (Fig. 15g) and the average canyon thalweg gradient (Fig. 15m).

The slope-break depth shows moderate scaling with maximum canyon depth (Fig. 15h) and maximum canyon sidewall steepness (Fig. 15q), and rather weak but statistically significant correlation with canyon length (Fig. 15b).

For the average slope gradient, moderate correlations are demonstrated with maximum canyon sidewall steepness (Fig. 15r) and average canyon thalweg gradient (Fig. 15o), whereas correlations with other parameters are weak and not significant (Fig. 15a-r).

#### 6.3.2. Interpretations

The canyon length is the only canyon morphometric parameter that is related to the continental-slope width, as reflected in the strong scaling between these two variables and, to a smaller extent, in the relationship between canyon length and slope-break depth.

Positive relationships are seen for slope width with maximum canyon width and depth, and for the latter with slope-break depth; these relationships reflect how intra-canyon erosion is promoted at the canyon mouth (see section 5.2.2.2).

The positive relationship between slope-break depth and maximum

canyon depth might also reflect how canyons in open seas tend to be deeper compared to canyons in semi-enclosed and enclosed seas (see section 7.4).

The results show that average canyon sinuosity is not correlated to the slope-break depth or to slope steepness. Additional data are needed to evaluate potential correlation between slope width and average canyon sinuosity.

The modest, positive correlation between the overall slope gradient and average canyon thalweg gradient relates to how the average canyon thalweg gradient is constrained by the average gradient of the continental slope; yet important variability is observed. In this study, as in previous ones (e.g. Harris and Whiteway, 2011), the overall canyon thalweg gradient is determined in part by the position of both canyon apex and mouth, which are themselves related to local seafloor relief. The observed moderate negative relationship between slope width and average canyon thalweg gradient reflects how wider slopes tend to display gentler gradients (Fig. 11; cf. Somme et al., 2009).

The moderate, positive scaling seen between maximum canyon sidewall steepness and the average slope gradient may reflect how slopes that are steeper on average may be associated with increased erosion in submarine canyons, in relation to steeper slopes promoting processes of mass failure (e.g. McGregor, 1983; Susanth et al., 2021), and potentially driving retrograde slope failure (Lo Iacono et al., 2014), as well as vertical canyon incision (e.g. Susanth et al., 2021). Following this line of interpretation, the negative correlation of slope width with maximum canyon sidewall steepness might be a record of the covariance between average slope gradient and slope width. An inverse moderate relationship is seen between slope-break depth and maximum canyon sidewall steepness, but the dataset does not include slope-break depths between 4,000 and 6,000 m bsl and dominantly includes canyons associated with continental-slope breaks that are 2,000 to 4,000 m bsl. More data are needed to confirm this relationship.

The lack of correlation between the average slope gradient and maximum canyon dimensions indicate that the average slope gradient has no significant influence on canyon size, in spite of how it might affect the magnitude of retrograde erosion and the erosive strength of down-canyon sediment gravity flows. Also, the average slope gradient does not capture local relief along the slope profiles, which can control sediment bypass (e.g. Soutter et al., 2021); further investigation of the role of slope relief and slope profile types as controls on canyon geomorphology is required.

## 7. Variations in canyon morphometric parameters across classes of environments

Descriptive statistics of frequency distributions of canyon morphometric parameters have been evaluated for the entire dataset (Fig. 16 a-f), as well as for separate groups of canyons reflecting categories of canyon-apex location relative to the shelf-break, continental-margin type, source-to-sink setting, oceanographic environment, and latitudinal zones (sections 7.1 to 7.5). This was done to investigate whether and how factors associated with the environmental setting may control canyon geomorphology. Meaningful comparisons of average canyon width and depth as a function of S2S system setting and latitudinal zone, and for average canyon depth relative to canyon-head location, were not possible due to limited data availability.

In addition, ratios of maximum width to maximum depth across the different environmental settings have been assessed (section 7.6).

The distributions of each canyon morphometric parameter are graphically presented in form of boxplots (Figs. 16–22) and are discussed in sections 7.1 to 7.6 below.

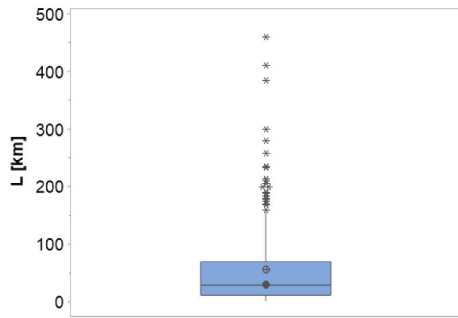
### 7.1. Canyon-apex location relative to the shelf break

#### 7.1.1. Observations

The studied shelf-incising canyons tend to be longer (Fig. 17a), more

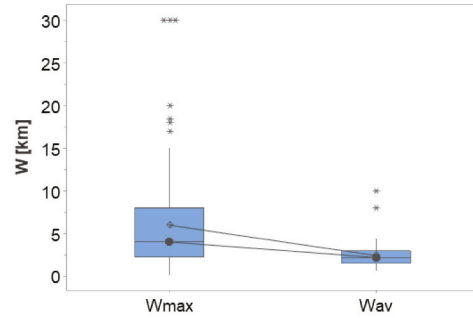


**A. Length**



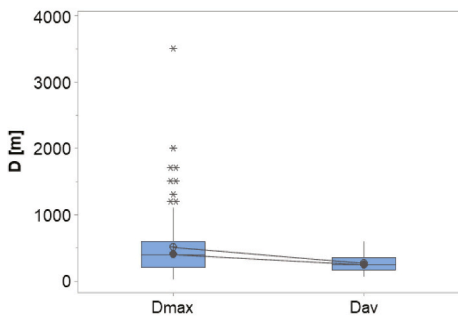
	N	min	mean	StDev	median	max
<b>L</b>	<b>263</b>	<b>2.00</b>	<b>56.52</b>	<b>69.15</b>	<b>29.79</b>	<b>460.00</b>

**B. Width**



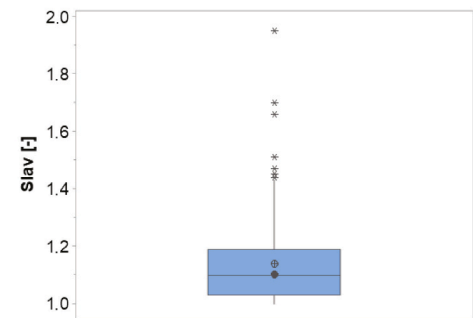
	N	min	mean	StDev	median	max
<b>Wmax</b>	<b>164</b>	<b>0.15</b>	<b>5.97</b>	<b>5.43</b>	<b>4.00</b>	<b>30.00</b>
<b>Wav</b>	<b>66</b>	<b>0.58</b>	<b>2.41</b>	<b>1.50</b>	<b>2.18</b>	<b>10.00</b>

**C. Depth**



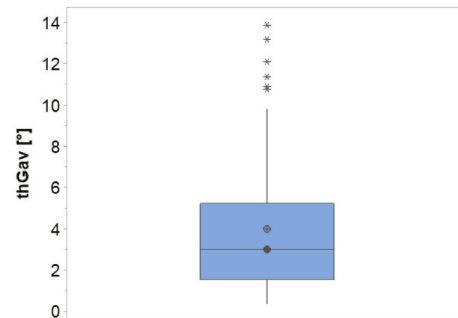
	N	min	mean	StDev	median	max
<b>Dmax</b>	<b>113</b>	<b>35.00</b>	<b>508.00</b>	<b>475.10</b>	<b>400.00</b>	<b>3500.00</b>
<b>Dav</b>	<b>52</b>	<b>70.00</b>	<b>268.10</b>	<b>126.30</b>	<b>244.00</b>	<b>594.00</b>

**D. Average canyon sinuosity**



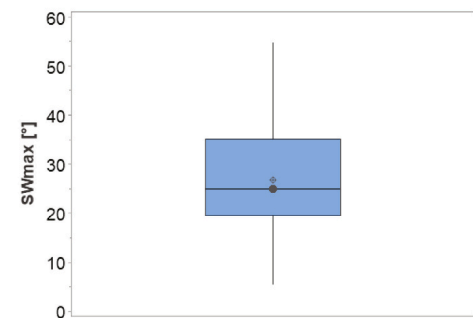
	N	min	mean	StDev	median	max
<b>Slav</b>	<b>151</b>	<b>1.00</b>	<b>1.14</b>	<b>0.15</b>	<b>1.1</b>	<b>1.95</b>

**E. Average canyon thalweg gradient**



	N	min	mean	StDev	median	max
<b>thGav</b>	<b>120</b>	<b>0.40</b>	<b>3.98</b>	<b>3.09</b>	<b>3.00</b>	<b>13.90</b>

**F. Maximum canyon sidewall steepness**



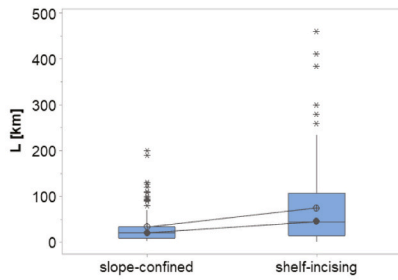
	N	min	mean	StDev	median	max
<b>SWmax</b>	<b>69</b>	<b>5.40</b>	<b>26.80</b>	<b>11.48</b>	<b>25.00</b>	<b>55.00</b>

**Fig. 16.** a-f: Boxplots of frequency distributions of the investigated canyon morphometric parameters.  $L$  = canyon length;  $W_{max}$  = maximum canyon width;  $W_{av}$  = average canyon width;  $D_{max}$  = maximum canyon depth;  $D_{av}$  = average canyon depth;  $Slav$  = average canyon sinuosity index;  $thG_{av}$  = average canyon thalweg gradient;  $SW_{max}$  = maximum canyon sidewall steepness. N = number of readings; min = minimum value; mean = mean value; StDev = standard deviation; median = median value; max = maximum value.

sinuous (Fig. 17f), and with larger average widths (Fig. 17c) than slope-confined canyons, on average by factors of 2.25, 1.09 and 1.52, respectively. Across these two groups, these are the morphometric parameters whose mean values differ significantly; differences are also seen in maximum canyon depth that are associated with p values that are just above the defined threshold of statistical significance. Although canyons incising the shelf display on average slightly greater maximum and overall widths, slope-confined canyons reach the same values (Fig. 17b&c), and the largest value of average width is associated with a

slope-confined canyon (Fig. 17c). Although greater maximum depths (Fig. 17d), and lower overall thalweg gradients (Fig. 17g) are seen in canyons incising the shelf, differences in their average values are not statistically significant. The data on average canyon depth are limited, but the results show very similar ranges in values across the two groups (Fig. 17e). On average, the maximum sidewall steepness is similar between groups of canyons classified on the location of the canyon apex relative to the shelf break, but slope-confined canyons display a greater range (Fig. 17h).

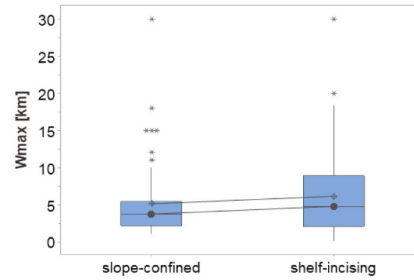
**A. Length**



	N	min	mean	StDev	median	max
<i>slope</i>	98	3.70	33.37	39.32	21.00	200.00
<i>shelf</i>	137	2.00	75.13	84.69	45.00	460.00

T-Value = -4.53 DF = 230 P-Value ≤ 0.001

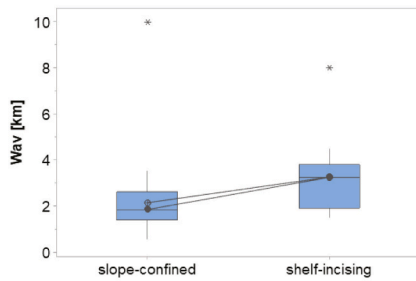
**B. Maximum width**



	N	min	mean	StDev	median	max
<i>slope</i>	64	1.00	5.12	4.96	3.74	30.00
<i>shelf</i>	87	0.15	6.14	5.32	4.79	30.00

T-Value = -0.44 DF = 148 P-Value = 0.658

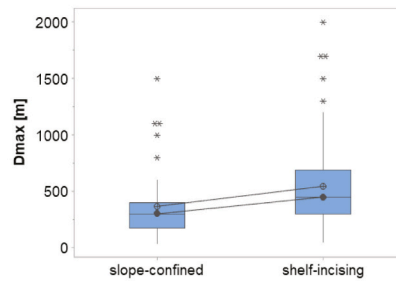
**C. Average width**



	N	min	mean	StDev	median	max
<i>slope</i>	45	0.58	2.15	1.41	1.85	10.00
<i>shelf</i>	17	1.51	3.26	1.58	3.25	8.00

T-Value = -3.42 DF = 31 P-Value = 0.002

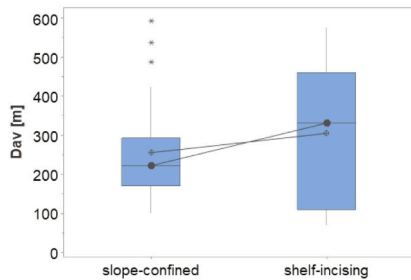
**D. Maximum depth**



	N	min	mean	StDev	median	max
<i>slope</i>	39	35.00	367.30	322.10	300.00	1500.00
<i>shelf</i>	65	50.00	545.10	410.10	450.00	2000.00

T-Value = -2.45 DF = 80 P-Value = 0.016

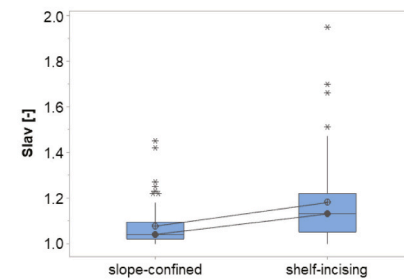
**E. Average depth**



	N	min	mean	StDev	median	max
<i>slope</i>	39	100.00	255.30	115.70	222.00	594.00
<i>shelf</i>	9	70.00	304.90	183.40	331.00	576.00

T-Value = -0.17 DF = 9 P-Value = 0.868

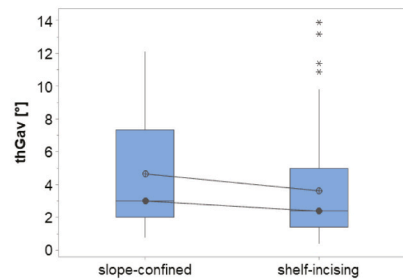
**F. Average canyon sinuosity**



	N	min	mean	StDev	median	max
<i>slope</i>	61	1.00	1.08	0.09	1.04	1.45
<i>shelf</i>	79	1.00	1.18	0.17	1.13	1.95

T-Value = -4.70 DF = 131 P-Value ≤ 0.001

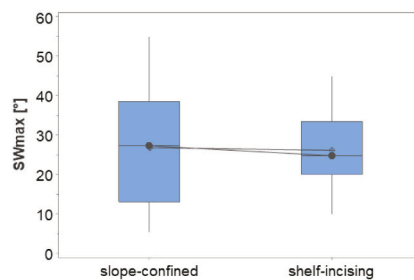
**G. Average canyon thalweg gradient**



	N	min	mean	StDev	median	max
<i>slope</i>	29	0.78	4.65	3.29	3.00	12.10
<i>shelf</i>	77	0.40	3.62	3.14	2.37	13.90

T-Value = 1.73 DF = 51 P-Value = 0.090

**H. Maximum canyon sidewall steepness**



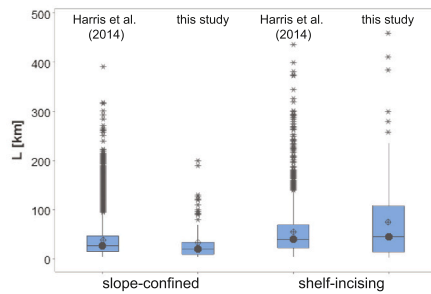
	N	min	mean	StDev	median	max
<i>slope</i>	30	5.40	26.82	13.92	27.30	55.00
<i>shelf</i>	38	10.00	26.18	8.68	24.80	45.00

T-Value = 0.22 DF = 46 P-Value = 0.825

**Fig. 17.** a-j: Boxplots of frequency distributions of canyon morphometric parameters for studied canyons classified on the location of the canyon apex relative to the shelf break into slope-confined (N=99) and shelf-incising canyons (N=154). I.&J. Boxplots of canyon length (I) and average depth (J) and results of statistical analyses plotted from the dataset of [Harris et al. \(2014\)](#) for calibration.  $L$  = canyon length;  $W_{max}$  = maximum canyon width;  $W_{av}$  = average canyon width;  $D_{max}$  =

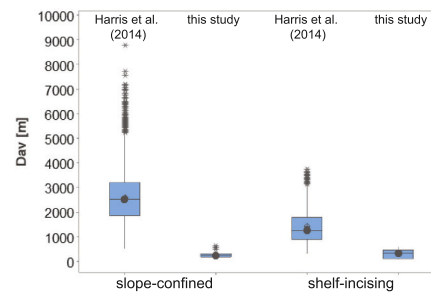
maximum canyon depth;  $D_{av}$  = average canyon depth;  $SI_{av}$  = average canyon sinuosity index;  $thG_{av}$  = average canyon thalweg gradient;  $SW_{max}$  = maximum canyon sidewall steepness. N = number of readings; min = minimum value; mean = mean value; StDev = standard deviation; median = median value; max = maximum value. Results of Two-Sample T-test: DF = degrees of freedom.

### I. Length (Harris et al., 2014)



	N	min	mean	StDev	median	max
<b>slope</b>	<b>7401</b>	4.10	37.29	33.38	26.92	391.34
<b>shelf</b>	<b>2076</b>	3.84	54.82	50.27	39.76	436.33
<b>T-Value = -18.16 DF = 3191 P-Value ≤ 0.001</b>						

### J. Average depth (Harris et al., 2014)



	N	min	mean	StDev	median	max
<b>slope</b>	<b>7401</b>	507.20	2563.50	978.40	2506.90	8770.30
<b>shelf</b>	<b>2076</b>	294.10	1395.00	657.60	1260.10	3746.00
<b>T-Value = 55.26 DF = 2972 P-Value ≤ 0.001</b>						

Fig. 17. (continued).

For the canyons studied by Harris et al. (2014), statistical tests reveal significant differences in mean values of length (Fig. 17i) and average depth (Fig. 17j) across the two groups. As in the canyons considered in our study, shelf-incising canyons are on average longer than their slope-confined counterparts, by a factor of 1.47, which is lower than what found in our study (2.25). Harris and Whiteway (2011) also reported mean values of canyon length; studied shelf-incising canyons with and without a river connection were on average 2.07 and 1.29 times longer, respectively, than canyons with their apex below the shelf break.

#### 7.1.2. Interpretations

The greater lengths of shelf-incising canyons may reflect how retrograde incision of the shelf and the promotion of canyon progradation by sediment gravity flows originating on the shelf and in the terrestrial catchment constitute primary controls on the length of submarine canyons. Sediment is supplied to the canyons via coupling with fluvial outlets or littoral cells and locally from within the shelf (sections 6.1 & 6.2). In addition, canyon heads placed above the storm wave-base can intercept sediment mobilised and transported during storm events (e.g. Sequeiros et al., 2019) (section 4.2.2). Our finding that shelf-incising canyons are on average longer than their slope-confined counterparts are in agreement with observations by Harris and Whiteway (2011) and Harris et al. (2014).

Harris et al. (2014) also show that shelf-incising canyons are on average twice as large in area compared to slope-confined canyons, whereas canyons of the latter group are on average almost twice as deep. However, for the canyons considered in this study, characteristics like the maximum width, maximum depth, average canyon thalweg gradient and maximum canyon sidewall steepness are not related to whether canyons are incised into the shelf. Thus, overall, the relative position of the canyon apex to the shelf break does not tie to these specific geomorphological characteristics. The results may however also reflect how some of the currently slope-confined canyons had a past connection to the shelf, now lost due to backfilling of their proximal parts (e.g. Pratson et al., 2007) and progradation of their heads (e.g., in relation to high sediment supply; cf. Mauffrey et al., 2015).

Slope-confined canyons can be fed by sands overpassing the shelf edge if their heads are in the range of the run-out distance of turbidity currents linked to fluvial discharge or littoral cells (e.g. Cronin et al., 2005; Yin et al., 2019). Canyons in high-latitude settings affected by glaciation can receive sediment delivered by the progradation of ice sheets onto shelf margins and from floating ice carrying debris (e.g. Gales et al., 2021). Sediment remobilised within the slope can also be

distributed to a slope-confined canyon by contour currents if the canyon is coupled with a contourite system (e.g. Wang et al., 2018; Warratz et al., 2019; Serra et al., 2020; Rodrigues et al., 2022, and references therein).

Despite the role of sediment gravity flows in canyon growth and sinuosity increase, mean values of average canyon sinuosity are very similar across the two groups. This indicates that the importance of connections of the canyon to the shelf as a control on its sinuosity might be limited, in contrast with current understanding. Specifically, the process of canyon shelf-breaching, by enabling linkages with shelf and terrestrial sediment sources, has been suggested to lead to distinctively higher sinuosities in shelf-incising canyons compared to slope-confined ones (e.g. Farre et al., 1983; Orange et al., 1994; Wiles et al., 2019). On this basis, the sinuosity of canyons has been utilised to deduct canyon head location relative to the shelf-break on a regional scale in absence of sufficient bathymetric data coverage of proximal parts of canyons (see Wiles et al., 2019). Based on our analyses, it appears that the overall canyon sinuosity is not a suitable predictor of the position of the canyon apex relative to the shelf break.

More generally, considering the findings of this work in light of those of earlier studies (Harris and Whiteway, 2011; Harris et al., 2014; Huang et al., 2014), it is concluded that whether a canyon is incised in the shelf is not a strong predictor of canyon geomorphology overall. Further investigation is necessary to determine the degree to which the volume of a canyon delimited by its 3D surface is related to the relative position of the canyon head on a global scale.

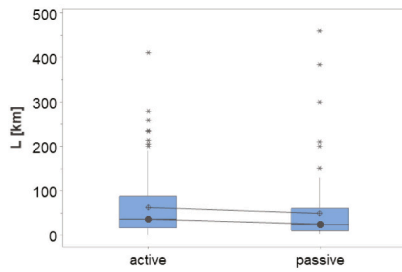
## 7.2. Continental-margin type

### 7.2.1. Observations

Submarine canyons located along passive margins tend to be overall deeper (Fig. 18e), have steeper thalwegs (Fig. 18g) and greater maximum sidewall steepness (Fig. 18h), with statistically significant differences in mean values. Groups of canyons associated with active and passive margins exhibit frequency distributions of maximum canyon dimensions (Figs. 18a, b & d) and average canyon sinuosity (Fig. 18f) that are rather similar. Studied active-margin canyons are on average longer (Fig. 18a) and overall wider (Fig. 18c). Average values for maximum canyon width (Fig. 18b) and depth (Fig. 18d) are almost identical across continental-margin types, but canyons from active margins display greater ranges in both morphometric parameters.

On average, continental slopes associated with studied canyons along passive margins tend to be significantly steeper than those along

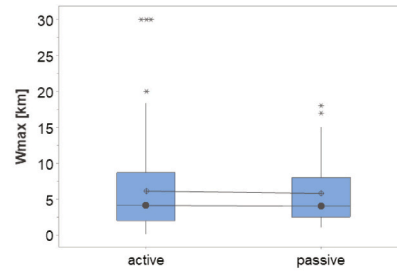
**A. Length**



	N	min	mean	StDev	median	max
<b>active</b>	141	2.00	62.90	69.85	36.00	411.00
<b>pass.</b>	122	3.16	49.15	67.87	24.71	460.00

**T-Value = 1.93 DF = 258 P-Value = 0.054**

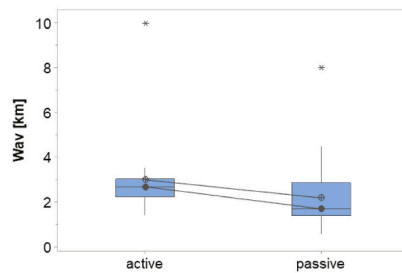
**B. Maximum width**



	N	min	mean	StDev	median	max
<b>active</b>	91	0.15	6.11	6.19	4.10	30.00
<b>pass.</b>	73	1.00	5.79	4.33	4.00	18.00

**T-Value = -1.02 DF = 159 P-Value = 0.308**

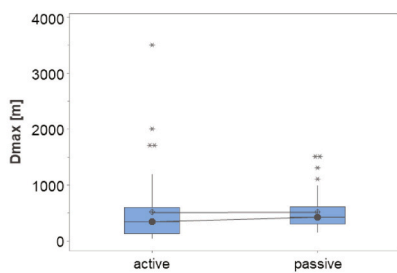
**C. Average width**



	N	min	mean	StDev	median	max
<b>active</b>	18	1.42	3.00	1.83	2.69	10.00
<b>pass.</b>	48	0.58	2.19	1.31	1.70	8.00

**T-Value = 2.96 DF = 39 P-Value = 0.005**

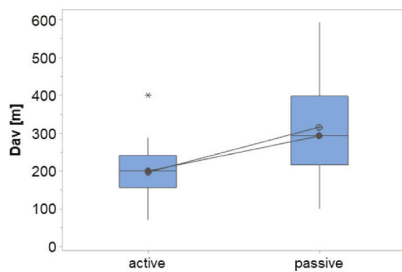
**D. Maximum depth**



	N	min	mean	StDev	median	max
<b>active</b>	60	35.00	505.40	584.40	340.00	3500.00
<b>pass.</b>	53	150.00	511.00	314.10	422.60	1500.00

**T-Value = -2.38 DF = 90 P-Value = 0.019**

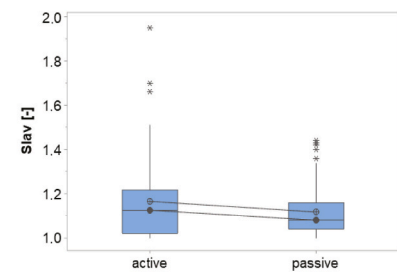
**E. Average depth**



	N	min	mean	StDev	median	max
<b>active</b>	21	70.00	196.70	71.10	200.00	400.00
<b>pass.</b>	31	100.00	316.40	133.20	293.00	594.00

**T-Value = -4.20 DF = 47 P-Value ≤ 0.001**

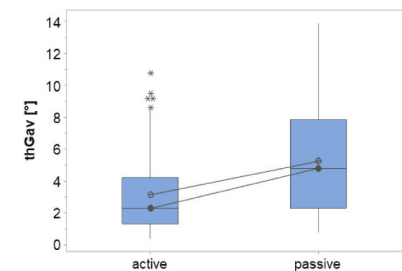
**F. Average canyon sinuosity**



	N	min	mean	StDev	median	max
<b>active</b>	68	1.00	1.17	0.19	1.13	1.95
<b>pass.</b>	83	1.00	1.12	0.11	1.08	1.44

**T-Value = 1.79 DF = 109 P-Value = 0.077**

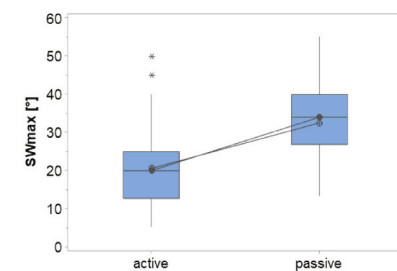
**G. Average canyon thalweg gradient**



	N	min	mean	StDev	median	max
<b>active</b>	72	0.40	3.13	2.47	2.28	10.773
<b>pass.</b>	48	0.80	5.24	3.50	4.80	13.90

**T-Value = -3.80 DF = 100 P-Value ≤ 0.001**

**H. Maximum canyon sidewall steepness**



	N	min	mean	StDev	median	max
<b>active</b>	33	5.40	20.60	10.78	20.00	50.00
<b>pass.</b>	36	13.40	32.50	8.95	34.00	55.00

**T-Value = -4.97 DF = 62 P-Value ≤ 0.001**

**Fig. 18.** a-h: Boxplots of frequency distributions of canyon morphometric parameters for studied canyons classified based on the continental-margin type into active-margin (N=153) and passive-margin canyons (N=129) (classification after Harris et al., 2014). See Fig. 17 for legend.

active margins ( $\sim 3.22^\circ$  vs.  $\sim 5.16^\circ$ , respectively; Two-sample t-test: T-Value: -4.13 DF= 70 P-Value  $\leq 0.001$ ;  $N_{\text{active}}= 44$ ;  $N_{\text{passive}}= 47$ ).

### 7.2.2. Interpretations

The results suggest that the margin type is not a primary predictor of maximum canyon dimensions or canyon sinuosity. Studied canyons along passive margins tend to display larger average depths and steeper canyon thalweg gradients compared to their active-margin counterparts, which tend to have greater average widths. The varied influence of the continental-margin type on different aspects of canyon geomorphology can be explained as follows:

The seafloor relief, which influences sediment transport pathways, hydrodynamic processes and canyon geomorphology, can be sculpted by different processes, which are not limited to one particular continental-margin setting: faulting, although prominent in active-margin environments can also occur along passive margins (e.g. [Osmundsen and Redfield, 2011](#)); diapirism can be variably linked to processes acting in both margin types, such as mud and salt movements.

Another aspect to consider is that the physiography of continental margins can vary significantly in both tectonic settings. Although continental shelves along passive margins tend to be wider and with gentler lower-shelf gradients compared to those of active margins (e.g. [Inman and Nordstrom, 1971](#); [Blum and Hattier-Womack, 2009](#); [Harris et al., 2014](#); [Harris and Macmillan-Lawler, 2016](#); [Nyberg et al., 2018](#)), other shelf morphotypes exist. For example, shelves associated with passive margins can be as narrow as those associated with active margins (e.g. [Harris and Macmillan-Lawler, 2016](#)). The continental slopes of active margins are, on average, 1.28 times narrower (36 km) than those of passive margins (46 km); maximum widths are 368 km and 254 km, respectively ([Harris et al., 2014](#)). Given the strong relationship between slope width and canyon length (see [section 6.3](#)), similarity in the ranges and mean values of canyon length for the two margin types may be partly related to the limited difference in slope width between active and passive margins. By contrast, the steeper average thalweg gradients of passive-margin canyons likely reflect how the average canyon thalweg gradient is related to the overall slope gradient (cf. [section 6.3](#)), and that in the dataset overall gradients of continental slopes associated with canyons along passive margins tend to be higher compared to those along active ones. Considering the observed variability in relationships between aspects of catchment, shelf and slope configuration and canyon morphometric parameters ([sections 6.2 & 6.3](#)), contrasting characteristics in margin physiography are not evidently tied to particular geomorphologic characteristics in canyons.

The tendency of canyons from passive margins to have greater maximum sidewall steepness compared to canyons in active-margin settings might be explained by the effect of recurrent seismic activity on the stabilisation of seafloor substrate: although active margins are characterised by recurrent and high-magnitude seismic activity, the occurrence of submarine mass-transport processes can be subdued (e.g. [Strozyk et al., 2010](#)). The influence of background seismic activity on slope stability and mass-transport processes is variable and complex: seismic strengthening by recurrent earthquakes has been proposed as an effective mechanism leading to slope stabilisation and a decrease in both scale and occurrence of slope-failure processes (e.g. [Strozyk et al., 2010](#); [Nelson et al., 2011](#); [Molenaar et al., 2019](#)). Recurrent seismic activity can decrease the potential oversteepening of slopes by inducing a steady remobilisation and redistribution of slope deposits ([Strozyk et al., 2010](#)). However, at the same time the magnitude of earthquakes controls mass-failure processes, whereby higher-magnitude earthquakes tend to trigger larger-scale slope failures (e.g. [Strozyk et al., 2010](#); [Molenaar et al., 2019](#)). Thus, slope failure may play a less important role in controlling canyon morphology on active margins compared to passive margins. Furthermore, earthquakes of small to high magnitudes do occur on passive margins (e.g. [Stein et al., 1989](#); [Wolin et al., 2012](#); [Katz and Hamiel, 2018](#)) and might act as a trigger of sediment remobilisation (e.g. [Katz and Hamiel, 2018](#)).

Our findings suggest that submarine-canyon geomorphology does not differ fundamentally between active and passive margins.

### 7.3. Source-to-sink system setting

#### 7.3.1. Observations

Submarine canyons in continental and insular settings display similar frequency distributions of canyon morphometric parameters. Between the two groups, mean values only differ by a factor 1.08 or lower, except for the average canyon thalweg gradient, which is on average 1.17 times greater in continental-setting canyons. Frequency distributions of average canyon width and depth could not be evaluated due to lack of data for insular canyons ([Fig. 19a-h](#)).

For studied canyons with a sediment connection to one or several fluvial systems, the size of associated terrestrial catchments tends to be markedly greater in continental settings – on average by a factor of  $\sim 100$  (341,842 km<sup>2</sup> compared to 3071 km<sup>2</sup>; Two-sample t-test: T-Value= 4.04 DF= 29 P-Value $\leq 0.001$ ;  $N_{\text{continental}}= 31$  and  $N_{\text{insular}}= 10$ ). Whereas more data is needed to corroborate this finding, the results demonstrate that continental catchments display a great variability in size; studied catchments vary from 84 km<sup>2</sup> to 3,800,000 km<sup>2</sup>. Insular shelves tend to be narrower and steeper than shelves offshore continental landmasses. The shelves of continental settings are on average 4.51 times wider than those of insular settings (108 km compared to 24 km; Two-sample t-test: T-Value=8.20 DF=56 P-Value $\leq 0.001$ ;  $N_{\text{continental}}= 166$  and  $N_{\text{insular}}= 37$ ). Mean overall shelf gradients of insular shelves at the canyon location are 1.8 times greater ( $0.756^\circ$  compared to  $0.420^\circ$ ; Two-sample t-test: T-Value=-3.21 DF= 33 P-Value= 0.003;  $N_{\text{continental}}= 96$  and  $N_{\text{insular}}= 21$ ).

#### 7.3.2. Interpretations

The results indicate that the association of a submarine canyon with a continental landmass or an island is not reflected in important differences in canyon geomorphology, with the caveat that relationships between S2S system setting and average canyon dimensions remain to be assessed. The similarity in frequency distributions and mean values for individual canyon morphometric parameters across the two groups might reflect how controlling factors are not significantly impacted by the S2S system setting, but also that different controls can generate similar geomorphologic characteristics in canyons across different S2S system settings.

The inherently limited extent of the terrestrial catchment in insular S2S systems compared to continental S2S systems does not appear to be a major factor for submarine canyon geomorphology. In part, this may be linked to the variability of the scale of islands, with large islands having potentially sizable catchments, and smaller catchments also occurring on continental landmasses.

For canyons associated with volcanic islands (97% of the investigated insular canyons in the study), volcanic activity may be the dominant source of sediment (e.g. [Aiello et al., 2020](#)). In such case, uplift and denudation rates are of lesser importance as controlling factors on sediment fluxes to canyons.

In addition, findings from the regional canyon study by [Smith et al. \(2017\)](#) indicate that the prevalence of igneous bedrock lithology in terrestrial source areas might inhibit canyon formation. In volcanic rocks, weathered clay minerals might enhance seafloor cohesion, whereas the lack of mud in plutonic bedrock might inhibit the development of turbidity currents ([Smith et al., 2017](#), and references therein). Hence, the transitioning of hyperpycnal flows (e.g. [Zhao et al., 2018](#)), dilute surface river plumes (e.g. [Hizzet et al., 2018](#)) and submarine mass failures (e.g. [Puig et al., 2014](#)) into turbidity currents might constitute a subordinate evolutionary process in canyons located in front of islands of a volcanic origin. On the other hand, the tendency of volcanic islands to experience slope failures along their flanks (e.g. [Le Bas et al., 2007](#); [Chang et al., 2021](#)) and shelf margins (e.g. [Quartau et al., 2015](#)) can supply sediment to a canyon by both individual large-scale failures (e.g.

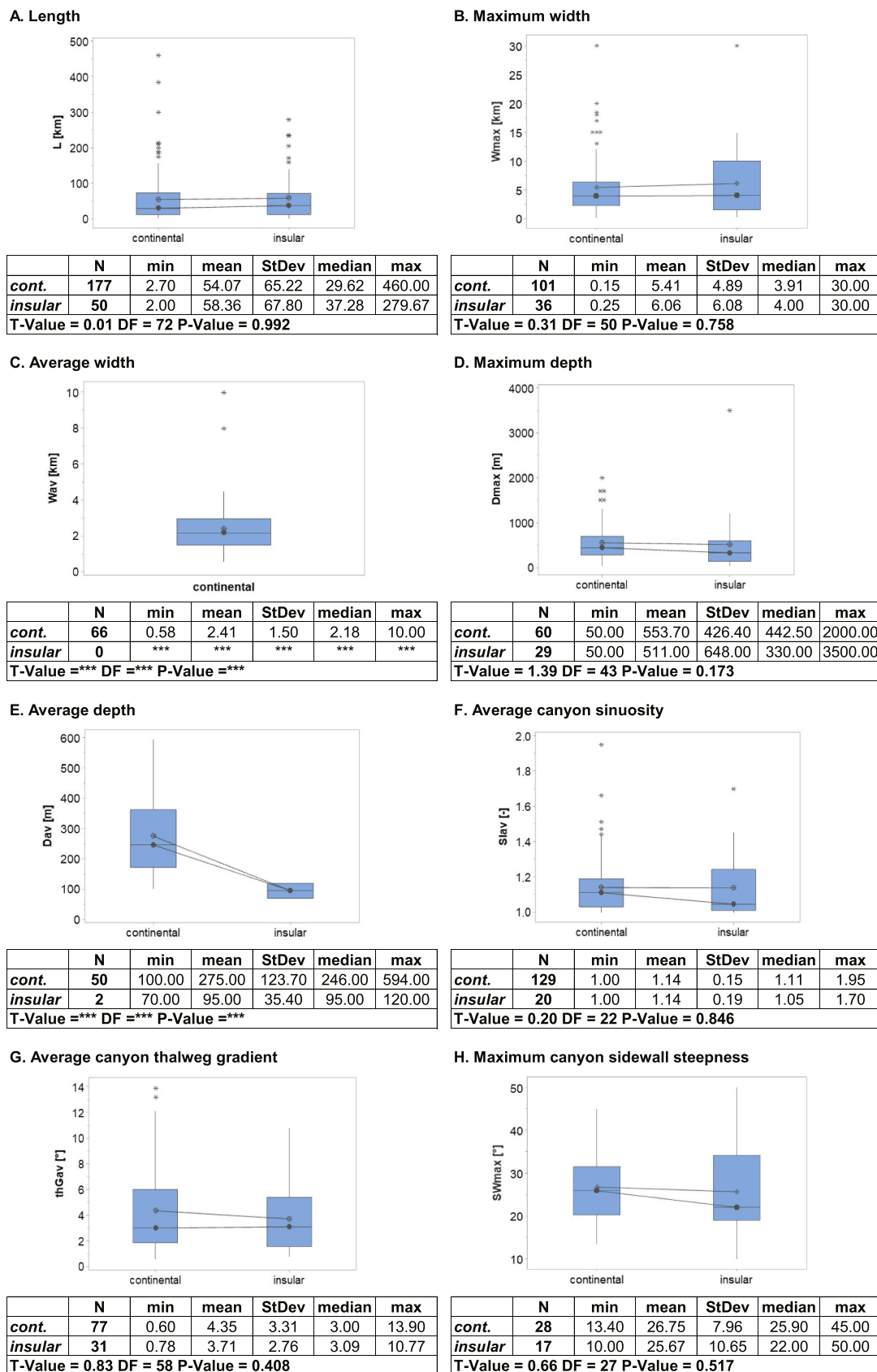


Fig. 19. a-h: Boxplots of frequency distributions of canyon morphometric parameters for studied canyons classified based on the source-to-sink setting into continental-margin (N=189) and insular canyons (N=57). \*\*\* denotes data paucity. See Fig. 17 for legend.

Le Bas et al., 2007) and high-frequency smaller failures (e.g. Chang et al., 2021). The importance of volcanic activity as a trigger for submarine slope failures, however, might be subordinate where other factors prevail, as storm events and onshore failure (Clare et al., 2018). Additionally, sediment transported by oceanic currents can represent a sustained source of sediment to insular canyons, independently of their origin.

Narrow and steep insular shelves promote sediment dispersal to the shelf margin, increased shear stress of sediment gravity flows, and shelfal sediment remobilisation (e.g. Hale et al., 2012; Babonneau et al., 2013). These factors may facilitate canyon activity, countering the effects of the reduced size of terrestrial catchments and limited seafloor erodibility.

#### 7.4. Oceanographic environment

##### 7.4.1. Observations

Distributions of canyon length (Fig. 20a), maximum width (Fig. 20b), average sinuosity (Fig. 20f) and average thalweg gradient (Fig. 20g) for open-sea canyons and canyons from semi-enclosed or enclosed seas are similar: apart from the thalweg gradient, the mean values of these parameters do not differ to a statistically significant level across the two groups. The average canyon width is greater for canyons located in semi-enclosed and enclosed seas compared to those in open seas, but this observation is based on a small dataset (Fig. 20c); conversely, the average depth of open-sea canyons is higher. The differences in mean values of average canyon depth and width across the two groups are only statistically significant for the former. In contrast, marked differences in distributions of maximum canyon depth are seen across the two groups: on average, the maximum canyon depth is 1.91 times higher in open-sea canyons (Fig. 20d). Open-sea canyons also tend to have steeper sidewalls than canyons from semi-enclosed and enclosed seas, by a factor of 1.73 on average (Fig. 20h). These differences are statistically significant.

Continental slopes located in open-sea settings have on average greater slope-break depths than continental slopes associated with semi-enclosed and enclosed seas (3959 m compared to 3072 m, respectively; T-Value=3.92 DF=98 P-Value<0.001;  $N_{\text{open sea}} = 85$ ;  $N_{\text{se\&e seas}} = 70$ ).

##### 7.4.2. Interpretations

The results suggest that conditions associated with the oceanographic environment may exert an influence on maximum canyon depth, the average canyon gradient and the steepness of canyon margins, but not on canyon length, maximum width and overall sinuosity.

Fundamental differences between the two environments lie in the scale of the water body, in its degree of confinement, and in the presence of thermohaline circulation and major oceanic currents in oceans (e.g. Rahmstorf, 2006; Faugères and Mulder, 2011). In contrast, upwelling and internal waves can affect canyons in both open-oceanic (e.g. Hickey, 1997; Smith et al., 2018) and semi-enclosed seas (e.g. Flexas et al., 2008; Li et al., 2022). Our findings might indicate that controlling factors that predominantly affect canyon geomorphology by acting along directions that are transverse to the canyon axis, like slope-parallel currents and lateral slope failures, might have a greater impact on canyon geomorphology in open seas. Oceanic currents might transport greater volumes of sand-sized sediment due to their greater extent and great depth range (e.g. Faugères and Mulder, 2011) compared to those in semi-enclosed and enclosed seas, which can be deposited onto intra-canyon ridges and canyon margins thereby increasing canyon depths and steepening canyon sidewalls by aggradation. Oversteepened margins are in turn more prone to collapse, which can lead to steeper margins over the affected area of the canyon.

The greater sidewall steepness of open-sea canyons might also reflect how the studied high-latitude (sections 5.3 & 7.5) and passive-margin canyons (section 7.2), which tend to have steeper margins, are dominantly located in open-sea settings.

It must be recognised, additionally, that the findings may emerge not because of causal relationships with processes associated with the oceanographic environment, but merely because of positive scaling between canyon depth and sidewall steepness (section 4).

#### 7.5. Latitudinal zones

Variations in canyon morphometric parameters are evaluated for latitudinal belts assigned to tropical (0-23.5°), temperate (23.5°-66.5°), and polar (>66.5°) zones. The dataset contains fewer data from canyons from polar latitudes compared to canyons in tropical and temperate zones; this reflects the paucity of investigations of high-latitude submarine canyons, despite the large number of canyons in the Arctic and Antarctic regions (see Harris and Whiteway, 2011; Harris et al., 2014). The arctic canyons in this study are from only two regions: the NW Norwegian margin (N=15) and the Barrow Canyon from the N Alaskan margin. Thus, the representativeness of the data is likely to be limited. Because of this geographic bias, differences in mean values of canyon morphometric parameters from tropical and temperate latitudes have been tested separately.

##### 7.5.1. Observations

Results of one-way ANOVA for canyons grouped by latitude range show statistically significant differences in mean values of length (Fig. 21a), maximum canyon width (Fig. 21b) and maximum canyon sidewall steepness (Fig. 21h), but not for maximum canyon depth (Fig. 21d).

Based on two-sample t-tests, statistically significant differences are seen for mean values of length (Fig. 21a) and average canyon sinuosity (Fig. 21f) between canyons of tropical and temperate latitudes. The difference in mean values of average canyon thalweg gradient is associated with a p value that is just above the threshold of statistical significance (Fig. 21g).

##### 7.5.2. Interpretations

The observed significant differences in canyon morphometrics may represent a record of latitude-related controls on aspects of canyon geomorphology. Considering the relationship between continental-slope gradient and average canyon thalweg gradient (section 6.3.2), the typically steeper thalwegs of tropical canyons, compared to temperate ones, might be related to the known latitudinal control on carbonate distribution to deep-marine environments (see Figure 3 of O'Mara and Dunne, 2019), in light of how carbonate can act to stabilise the slope substrate by binding and cementation (e.g. Adams and Kenter, 2013, and references therein).

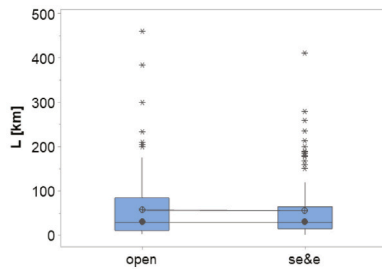
Based on the results of the statistical analyses, submarine canyons do not vary markedly across tropical and temperate latitudinal zones with regards to their maximum width and depth, maximum sidewall steepness, or average sinuosity. Limited latitudinal variations in canyon sinuosity are also documented in the geographic regions examined by Harris and Whiteway (2011).

In contrast, both oversteepening of canyon margins related to high and dispersed sediment supply from glaciated margins (e.g. Martinsen, 2005; Armitage et al., 2010; Gales et al., 2021) and gravitational slope failure from ice loading (Mulder and Moran, 1995) may cause canyon sidewalls to be steeper in high-latitude settings compared to low- and mid-latitude ones. Yet any such inference has to be viewed with caution (see section 5.3 for a more detailed discussion).

#### 7.6. Width-to-depth ratios

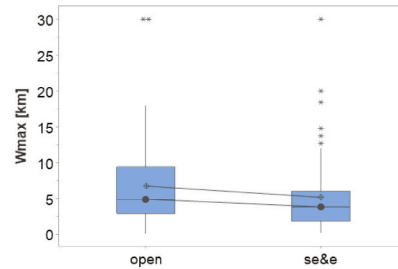
To investigate potential relationships between the ratio between maximum canyon width to maximum canyon depth ( $w_{d_{max}}$ ) and environmental factors, 100 submarine canyons of the study for which both maximum width and depth values have been obtained have been considered; aspect ratios have been evaluated for canyons across classes

**A. Length**



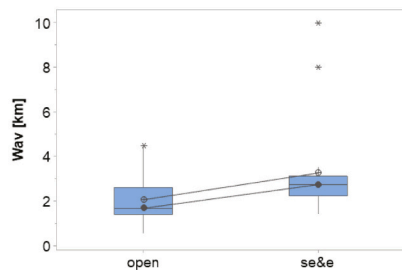
	N	min	mean	StDev	median	max
<b>open</b>	146	2.70	57.10	70.36	29.85	460.00
<b>se&amp;e</b>	117	2.00	55.80	67.91	29.79	411.00
<b>T-Value = -0.23 DF = 253 P-Value = 0.816</b>						

**B. Maximum width**



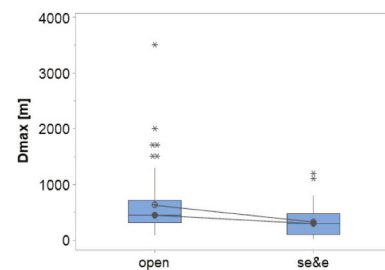
	N	min	mean	StDev	median	max
<b>open</b>	84	0.15	6.73	5.72	4.92	30.00
<b>se&amp;e</b>	80	0.25	5.16	5.02	3.83	30.00
<b>T-Value = 2.34 DF = 159 P-Value = 0.020</b>						

**C. Average width**



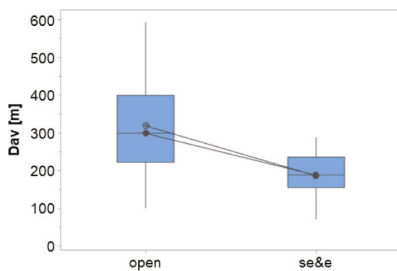
	N	min	mean	StDev	median	max
<b>open</b>	47	0.58	2.06	1.00	1.68	4.48
<b>se&amp;e</b>	19	1.42	3.26	2.12	2.74	10
<b>T-Value = -3.50 DF = 34 P-Value = 0.001</b>						

**D. Maximum depth**



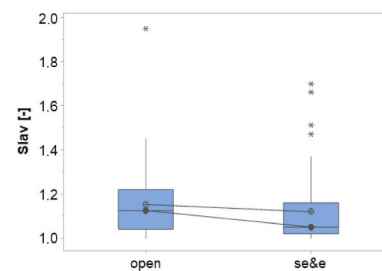
	N	min	mean	StDev	median	max
<b>open</b>	68	100.00	627.50	540.70	450.00	3500.00
<b>se&amp;e</b>	45	35.00	327.40	271.90	297.00	1200.00
<b>T-Value = 4.74 DF = 74 P-Value ≤ 0.001</b>						

**E. Average depth**



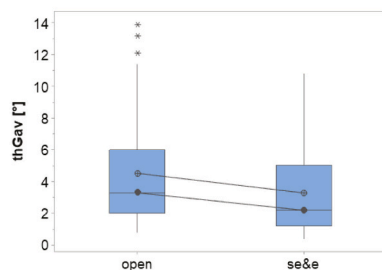
	N	min	mean	StDev	median	max
<b>open</b>	32	100.00	319.00	131.90	299.00	594.00
<b>se&amp;e</b>	20	70.00	186.50	55.20	188.00	289.00
<b>T-Value = 5.03 DF = 45 P-Value ≤ 0.001</b>						

**F. Average canyon sinuosity**



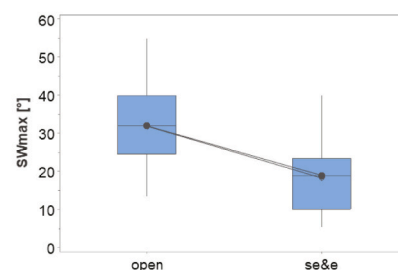
	N	min	mean	StDev	median	max
<b>open</b>	88	1.00	1.15	0.15	1.13	1.95
<b>se&amp;e</b>	63	1.00	1.12	0.15	1.05	1.70
<b>T-Value = 1.49 DF = 133 P-Value = 0.139</b>						

**G. Average canyon thalweg gradient**



	N	min	mean	StDev	median	max
<b>open</b>	67	0.80	4.53	3.22	3.30	13.90
<b>se&amp;e</b>	53	0.40	3.28	2.79	2.19	10.77
<b>T-Value = 2.95 DF = 99 P-Value = 0.004</b>						

**H. Maximum canyon sidewall steepness**

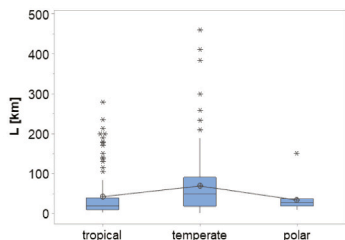


	N	min	mean	StDev	median	max
<b>open</b>	43	13.40	31.93	9.59	32.00	55.00
<b>se&amp;e</b>	26	5.40	18.32	9.17	19.00	40.00
<b>T-Value = 5.87 DF = 54 P-Value ≤ 0.001</b>						

**Fig. 20.** a-h: Boxplots of frequency distributions of canyon morphometric parameters for studied canyons classified based on the oceanographic environment into canyons associated with open seas (N=162) and semi-enclosed and enclosed seas (N=120). See Fig. 17 for legend.

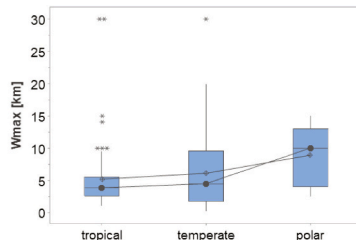


**A. Length**



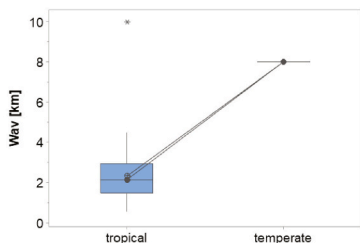
	N	min	mean	StDev	median	max
tropical	108	3.16	42.48	59.48	19.57	279.67
temper.	139	2.00	69.99	76.34	50.93	460.00
polar	16	10.00	34.31	32.30	28.00	150.00
F-Value = 9.62		DF1 = 2	DF2 = 53.2955	P-Value ≤ 0.001		
T-Value* = -4.39		DF = 234		P-Value ≤ 0.001		

**B. Maximum width**



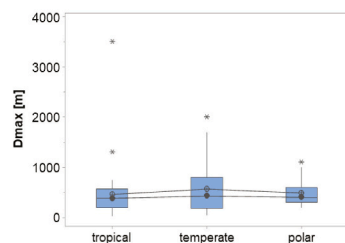
	N	min	mean	StDev	median	max
tropical	70	1.00	5.19	5.12	3.85	30.00
temper.	79	0.15	6.09	5.70	4.49	30.00
polar	15	2.50	8.90	4.61	10.00	15.00
F-Value = 6.86		DF1 = 2	DF2 = 43.3839	P-Value = 0.003		
T-Value* = 0.42		DF = 132		P-Value = 0.675		

**C. Average width**



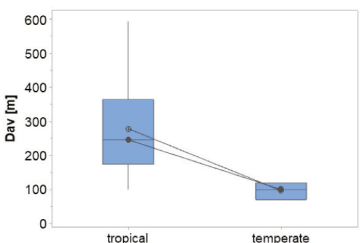
	N	min	mean	StDev	median	max
tropical	65	0.58	2.32	1.339	2.14	10.00
temper.	1	8.00	8.00	***	8.00	8.00
polar	0	***	***	***	***	***
F-Value = ***		DF1 = ***	DF2 = ***	P-Value = ***		
T-Value* = ***		DF = ***		P-Value = ***		

**D. Maximum depth**



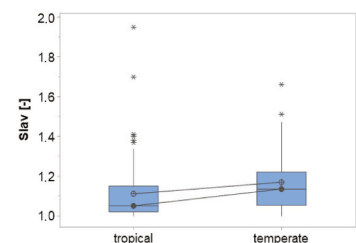
	N	min	mean	StDev	median	max
tropical	49	35.00	458.30	504.20	380.40	3500.00
temper.	49	50.00	564.20	494.60	425.00	2000.00
polar	15	200.00	486.70	274.20	400.00	1100.00
F-Value = 1.14		DF1 = 2	DF2 = 53.2580	P-Value = 0.328		
T-Value* = -0.65		DF = 93		P-Value = 0.518		

**E. Average depth**



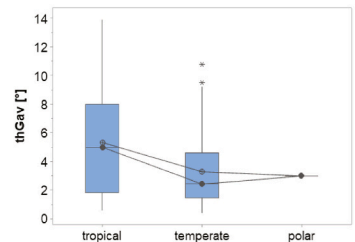
	N	min	mean	StDev	median	max
tropical	49	100.00	278.60	122.30	246.00	594.00
temper.	3	70.00	96.70	25.20	100.00	120.00
polar	0	***	***	***	***	***
F-Value = ***		DF1 = ***	DF2 = ***	P-Value = ***		
T-Value* = ***		DF = ***		P-Value = ***		

**F. Average canyon sinuosity**



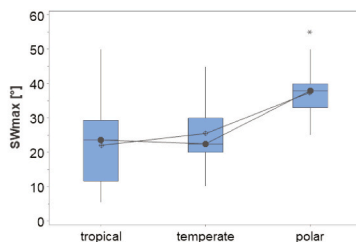
	N	min	mean	StDev	median	max
tropical	79	1.00	1.11	0.16	1.05	1.95
temper.	72	1.00	1.17	0.1395	1.14	1.66
polar	0	***	***	***	***	***
F-Value = ***		DF1 = ***	DF2 = ***	P-Value = ***		
T-Value* = -2.77		DF = 148		P-Value = 0.006		

**G. Average canyon thalweg gradient**



	N	min	mean	StDev	median	max
tropical	41	0.60	5.33	3.78	5.00	13.90
temper.	78	0.40	3.28	2.42	2.42	10.77
polar	1	2.98	2.98	***	2.98	2.98
F-Value = ***		DF1 = ***	DF2 = ***	P-Value = ***		
T-Value* = 2.61		DF = 69		P-Value = 0.011		

**H. Maximum canyon sidewall steepness**



	N	min	mean	StDev	median	max
tropical	26	5.40	22.06	12.02	23.60	50.00
temper.	28	10.00	25.50	8.94	22.50	45.00
polar	15	25.00	37.47	7.82	38.00	55.00
F-Value = 19.48		DF1 = 2	DF2 = 42.4993	P-Value ≤ 0.001		
T-Value* = -1.84		DF = 37		P-Value = 0.074		

**Fig. 21.** a-h: Boxplots of frequency distributions of canyon morphometric parameters for studied canyons classified based on latitudinal zones into tropical (N=117), temperate (N=149) and polar canyons (N=16). \* indicates that two-sample-t-tests have been conducted for canyons in tropical versus temperate latitudinal zones. N = number of readings; min = minimum value; mean = mean value; StDev = standard deviation; median = median value; max = maximum value. Results of Welch's ANOVA test: DF 1 = degrees of freedom numerator; DF 2 = degrees of freedom denominator. Results of Two-Sample T-test: DF = degrees of freedom; \*\*\* denotes data paucity.

of environments (Fig. 22a-f).

### 7.6.1. Observations

Although  $w_{d_{max}}$  ratios for the studied canyons vary over a broad range (2.45 to 73.33), mean and median values of  $w_{d_{max}}$  ratios are in the order of magnitude of  $10^1$  both for the whole dataset as well as for canyons grouped according to environmental factors. Mean values range between 11 and 20, and only differ significantly from each other for canyons in open seas versus semi-enclosed and enclosed seas (Fig. 22e). For canyons grouped into tropical, temperate and polar latitudinal zones, the difference in mean values yields a p-value of 0.011 (Fig. 22f).

### 7.6.2. Interpretations

The narrow range in mean and median  $w_{d_{max}}$  ratios and the lack of significant differences in mean values for the majority of canyon environmental classes indicate that maximum width-to-maximum depth ratios in canyons are of limited diagnostic value for inferring the environmental settings. This might reflect that width-to-depth ratios in canyons are not particularly sensitive to environmental controls and that they may inherently scale with processes that control canyon geomorphology globally. This would imply that width-to-depth ratios in submarine canyons are predominantly controlled by canyon self-organisation and autogenic processes, from the interplay of canyon-floor and margin aggradation and wall failure with intra-canyon sediment gravity flows, as suggested for submarine channels by Shumaker et al. (2018).

The inferred influence of the oceanographic environment on canyon width-to-depth ratios might reflect the way in which both erosional and depositional processes that operate along canyon margins are more strongly affected by the hydrodynamic regime in open seas than semi-enclosed and enclosed ones (see discussion in section 7.4).

## 8. Summary and conclusions

To increase understanding of the factors that exert control on canyon geomorphology and their relative importance on a global scale, statistical analyses were conducted to evaluate relationships between canyon morphometric parameters, and between these and attributes describing the physiographic setting of the canyon, including characteristics of elements of the source-to-sink (S2S) system (catchment, shelf and slope), the bathymetric setting of the canyon and its distance to the shoreline, the canyon-apex location relative to the shelf-break, the continental-margin type, the oceanographic environment, and the latitude of the canyon apex. In addition, selected morphometric parameters describing submarine canyons have been quantitatively characterised, both on a global scale and for different environmental settings (canyon-apex location relative to the shelf-break, continental-margin type, source-to-sink system setting, oceanographic environment and climate zones). Certain forms of scaling in attributes of canyon geomorphology are recognisable on a global scale and across different environmental settings and source-to-sink system configurations (Fig. 23a&b and Fig. 24a&b).

Key findings of the study are as follows:

- (1) Scaling relationships between canyon morphometric attributes tend to be weak, due to the varied influence of environmental allogenic controls and autogenic processes influencing canyon geomorphology. Nevertheless, despite specific regional or local conditions, some scaling relationships between canyon morphometric attributes are more likely recognisable on a global scale than others; these include, for example, scaling between maximum canyon dimensions, or between maximum sidewall steepness and maximum canyon width and depth.
- (2) The tendency of canyons to have greater maximum widths and depths with increasing canyon-mouth seafloor depth, the overall weakness in scaling of canyon morphometry with the terrestrial

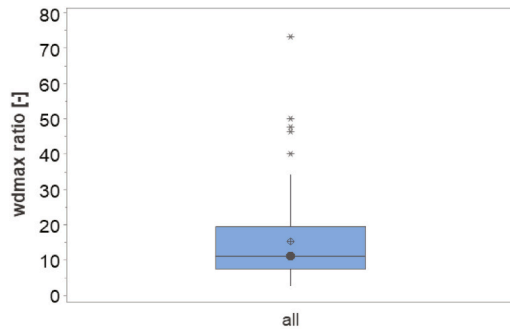
catchment and continental shelf, and the steeper canyon walls seen in canyons associated with open-sea settings compared to canyons in semi-enclosed or enclosed seas, possibly reflect how hydrodynamic processes such as upwelling, longshore drifts and along-slope currents influence canyon geomorphology.

- (3) Canyon morphometric parameters may reflect the interplay of different environmental factors. Hence, controls on canyon geomorphology cannot be described by generic models linking geomorphological characteristics to individual environmental parameters. Potential controls on certain canyon morphometric parameters include: the location of the canyon head relative to the shelf break, the continental-margin type, the oceanographic environment, the absolute latitude of the canyon apex, and the depth of the associated shelf break. Data on canyon length, sinuosity, thalweg gradient and maximum sidewall steepness indicate that these morphometric aspects are likely influenced by several environmental controls.

Key findings regarding relationships between the environmental setting and canyon geomorphology include:

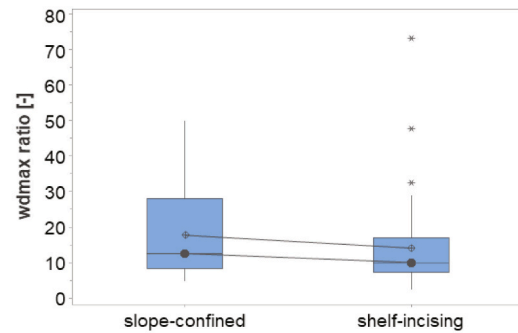
- (i) Maximum canyon dimensions and overall canyon sinuosity cannot be used to predict the position of the canyon apex relative to the shelf break and vice versa; this challenges concepts linking higher overall sinuosities in canyons to incision of the canyon into the shelf (e.g. Farre et al., 1983; Jobe et al., 2011; Wiles et al., 2019).
- (ii) The tendency of passive-margin canyons to develop steeper sidewalls compared to those of active-margin canyons indicates that slope failure might be generally less important for canyons from active margins compared to passive-margin ones, perhaps due to recurrent seismic strengthening of the seafloor substrate, which might act to inhibit mass failures, with the exception of mass failures triggered by high-magnitude earthquakes (e.g. Strozyk et al., 2010; Molenaar et al., 2019).
- (iii) Whether a submarine canyon is associated with a continental or insular setting does not exert control on overall canyon geomorphology. Volcanic sediment sources and narrow and steep insular shelves might compensate for the impact of smaller associated terrestrial catchments on sediment supply to submarine canyons, and for the potential effect igneous bedrock lithology might have on canyon evolution along volcanic islands by affecting seafloor erodibility and the erosive strengths of flows (Smith et al., 2017, and references therein).
- (iv) The complex interrelationships between climate-controlled processes are reflected in the weakness of linear and monotonic scaling of latitude with canyon morphometrics and can explain why the latitudinal position of a canyon is not a reliable indicator of overall canyon geomorphology in canyons in tropical and temperate latitudes. The complex role of climate influence on sediment sourcing and dispersal along glaciated continental margins, paired with the effect of ice loading on triggering of mass failures, might explain the observed steeper margins of submarine canyons from higher latitudes. However, in view of geographic bias and the limited sample size, it is possible that the results reflect how the studied higher-latitude canyons are coincidentally associated with passive-margin and open-sea settings, which tend to be associated with distinct distributions in sidewall steepness.
- (v) Mean values of maximum width-to-maximum depth ratios in canyons are consistently in the order of magnitude of  $10^1$  for all investigated canyon classes – regardless of canyon-head location relative to the shelf break, the tectonic-margin type, the S2S setting, the oceanographic environment and the latitudinal zone – albeit with significant global variability in documented values. This might reflect how width-to-depth ratios in submarine

**A. Dataset**



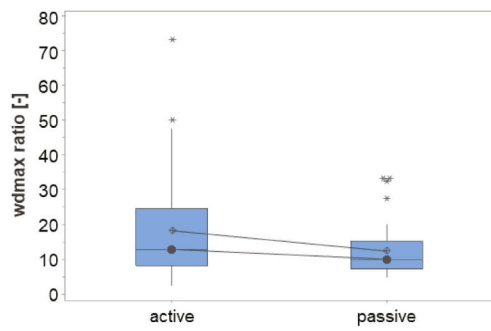
	N	min	mean	StDev	median	max
<b>all</b>	<b>100</b>	2.45	15.25	11.62	11.09	73.33

**B. Canyon-apex location**



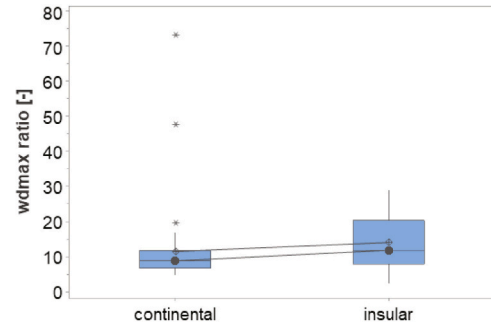
	N	min	mean	StDev	median	max
<b>slope</b>	<b>37</b>	4.65	17.67	12.37	12.50	50.00
<b>shelf</b>	<b>55</b>	2.45	14.05	11.59	10.00	73.33
<b>T-Value = 1.57</b>		<b>DF = 73</b>		<b>P-Value = 0.120</b>		

**C. Continental-margin type**



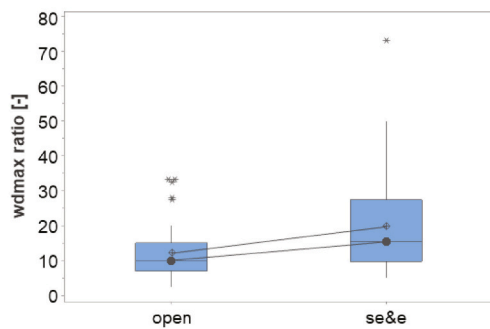
	N	min	mean	StDev	median	max
<b>active</b>	<b>50</b>	2.45	18.20	14.31	12.83	73.33
<b>pass.</b>	<b>50</b>	4.65	12.30	7.07	10.00	33.33
<b>T-Value = 2.02</b>		<b>DF = 84</b>		<b>P-Value = 0.046</b>		

**D. Source-to-sink setting**



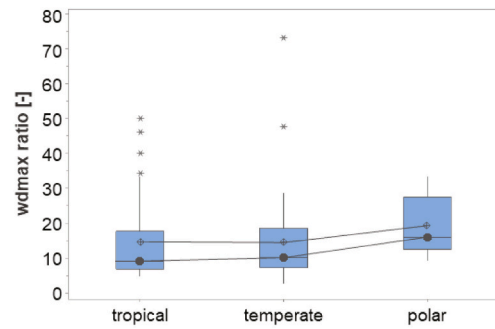
	N	min	mean	StDev	median	max
<b>cont.</b>	<b>48</b>	4.65	11.45	11.16	8.78	73.33
<b>insular</b>	<b>29</b>	2.45	14.00	7.64	11.82	28.86
<b>T-Value = -1.59</b>		<b>DF = 50</b>		<b>P-Value = 0.119</b>		

**E. Oceanographic environment**



	N	min	mean	StDev	median	max
<b>open</b>	<b>58</b>	2.45	12.06	7.19	10.00	33.33
<b>se&amp;e</b>	<b>42</b>	5.00	19.66	14.82	15.33	73.33
<b>T-Value = -3.06</b>		<b>DF = 73</b>		<b>P-Value = 0.003</b>		

**F. Latitudinal zones**



	N	min	mean	StDev	median	max
<b>tropic.</b>	<b>44</b>	4.65	14.65	11.45	9.12	50.00
<b>temp.</b>	<b>41</b>	2.45	14.43	12.67	10.10	73.33
<b>polar</b>	<b>15</b>	9.09	19.27	8.53	16.00	33.33
<b>F-Value = 4.96</b>		<b>DF1 = 2</b>		<b>DF2 = 46.7627</b>		<b>P-Value = 0.011</b>
<b>T-Value* = 0.21</b>		<b>DF = 81</b>		<b>P-Value = 0.836</b>		

Fig. 22. a-f: Boxplots of frequency distributions of maximum-width-to-maximum-depth ( $w_{dmax}$ ) ratios in studied canyons A. for the dataset and B.-F. across classes of environments. \* indicates that two-sample-t-tests have been conducted for canyons in tropical versus temperate latitudinal zones. See Fig. 21 for legend.

### A. Relationships between canyon morphometrics

#### Linear monotonic relationships

	L	Wmax	Wav	Dmax	Dav	Slav	thGav	SWmax
L		0.5	0.8	0.5		0.5	-0.5	
Wmax	0.5		0.8	0.8	0.5	0.4	-0.3	0.4
Wav	0.8	0.8		0.8				
Dmax	0.5	0.8	0.8		1.0			0.4
Dav		0.5		1.0		0.5		***
Slav	0.5	0.4			0.5		-0.3	
thGav	-0.5	-0.3						
SWmax		0.4		0.4	***			

#### Non-linear monotonic relationships

	L	Wmax	Wav	Dmax	Dav	Slav	thGav	SWmax
L		0.6	0.6	0.7		0.5	-0.7	0.3
Wmax	0.6		0.8	0.7		0.4	-0.4	0.4
Wav	0.6	0.8		0.8				
Dmax	0.7	0.7	0.8		1.0			0.4
Dav				1.0		0.5		***
Slav	0.5	0.4			0.5		-0.4	
thGav	-0.7	-0.4						
SWmax	0.3	0.4		0.4	***			

### B. Relationships between canyon morphometrics and environmental parameters

#### Linear monotonic relationships & differences between canyon groups

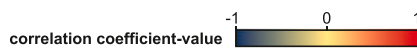
	Lfls	Qfls	Aflsc	Hflsc	Wsh	Dsh	Gsh	Wsl	Dsl	Gsl	Dismin	SDmin	SDmax	Latabs
L				0.4	0.2	0.4		0.4					0.6	
Wmax				0.6		0.4		0.4					0.4	0.2
Wav	***	***	***	***		0.5	0.7							0.5
Dmax						0.4		0.4	0.6				0.8	
Dav	***	***	***	***								-0.4	0.7	-0.4
Slav				0.6		0.4		***					0.6	
thGav		***				-0.3				0.5			-0.3	-0.4
SWmax	***	***	***	***	0.6					0.8	-0.3		0.4	0.5

cnh. location	margin type	S2S setting	ocean. env.	lat. (ANOVA)	lat. (t-test)	sh. depth 120	sh. depth 130
X				X	X	X	X
				X			
X	X	***	X	***	***	***	***
			X			X	X
***	X	***	X	***	***	***	***
X				***	X	X	X
	X		X	***		X	X
	X		X	X			

#### Non-linear monotonic relationships & differences between canyon groups

	Lfls	Qfls	Aflsc	Hflsc	Wsh	Dsh	Gsh	Wsl	Dsl	Gsl	Dismin	SDmin	SDmax	Latabs
L		0.7		0.6	0.2	0.5		0.9	0.4				0.7	0.3
Wmax			0.6	0.6				0.7					0.5	0.2
Wav	***	***	***	***	0.4	0.6	0.6			0.4				0.5
Dmax	0.7	***	0.7	***	0.4			0.6	0.5			-0.4	0.8	
Dav	***	***	***	***		***						-0.4	0.7	-0.4
Slav		0.5		0.6	-0.3	0.4		***			-0.3	-0.3	0.5	0.2
thGav		***				-0.3		-0.5		0.5				-0.3
SWmax	***	***	***	***	0.5				-0.6	0.7			0.4	0.4

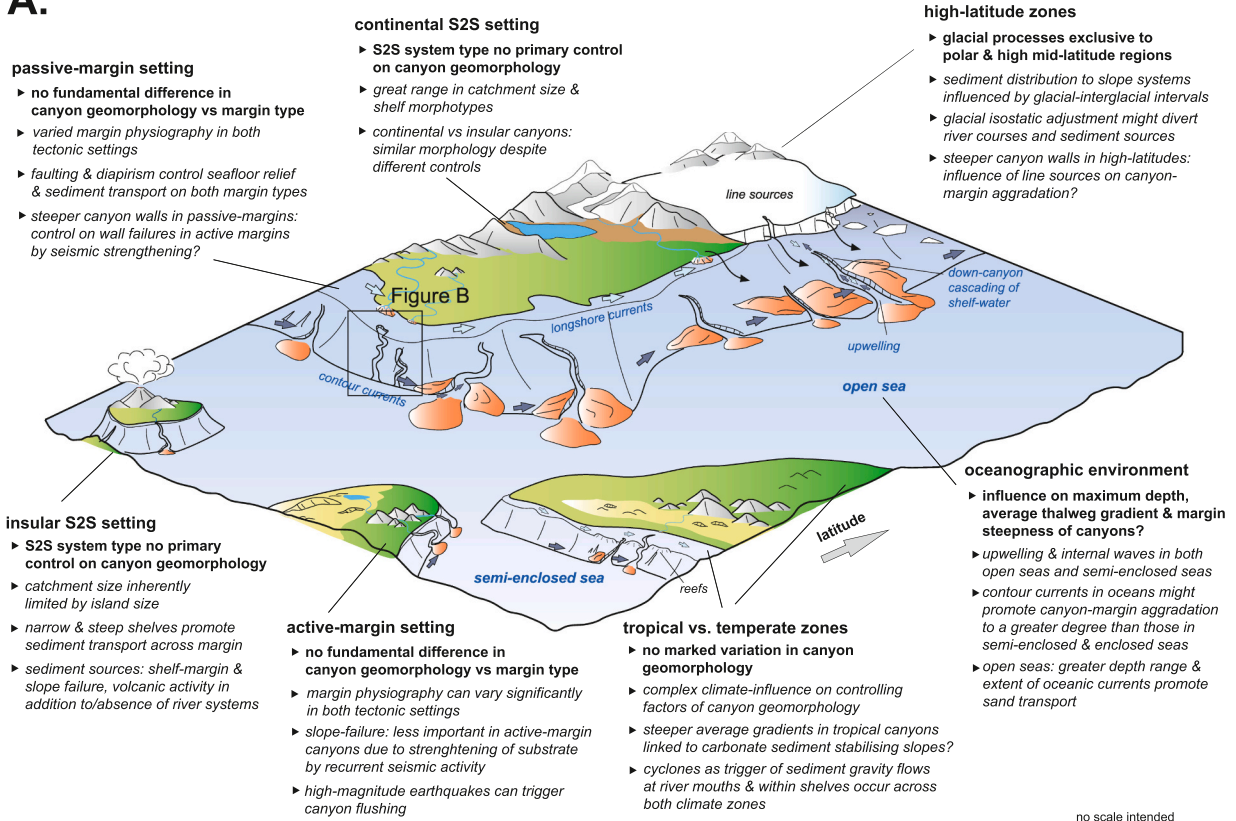
cnh. location	margin type	S2S setting	ocean. env.	lat. (ANOVA)	lat. (t-test)	sh. depth 120	sh. depth 130
X				X	X	X	X
				X			
X	X	***	X	***	***	***	***
			X			X	X
***	X	***	X	***	***	***	***
X				***	X	X	X
	X		X	***		X	X
	X		X	X			



X difference in mean values between canyon groups is statistically significant (p<0.01)  
 \*\*\* not enough data

Fig. 23. a&b: Summary tables displaying relationships of canyon morphometric parameters A. with each other and B. with environmental parameters for results of the correlation analyses and statistical tests with a statistical significance (p<0.01) and N>=15 for each parameter and canyon group. L = canyon length; Wmax = maximum canyon width; Wav = average canyon width; Dmax = maximum canyon depth; Dav = average canyon depth; Slav = average canyon sinuosity index; thGav = average canyon thalweg gradient; SWmax = maximum canyon sidewall steepness; Lfls = fluvial system length; Qfls = average annual fluvial discharge; Aflsc = size of the catchment; Hflsc = maximum elevation in the catchment area; Wsh = shelf width; Dsh = shelf-break depth; Gsh = average shelf gradient; Wsl = slope width; Dsl = slope-break depth; Gsl = average slope gradient; Dismin = minimum distance between the canyon and shoreline; SDmin = minimum seafloor depth at the canyon; SDmax = maximum seafloor depth at the canyon; Latabs = absolute value of the latitude of the canyon apex; cnh. location= canyon-apex location relative to the shelf-break; margin type = continental-margin type; ocean. env. = oceanographic environment; lat. = latitude at the canyon apex; sh. Depth = shelf break depth at the canyon. \*\*\* denotes datasets that were deemed too small for statistical analyses.

**A.**



**B.**

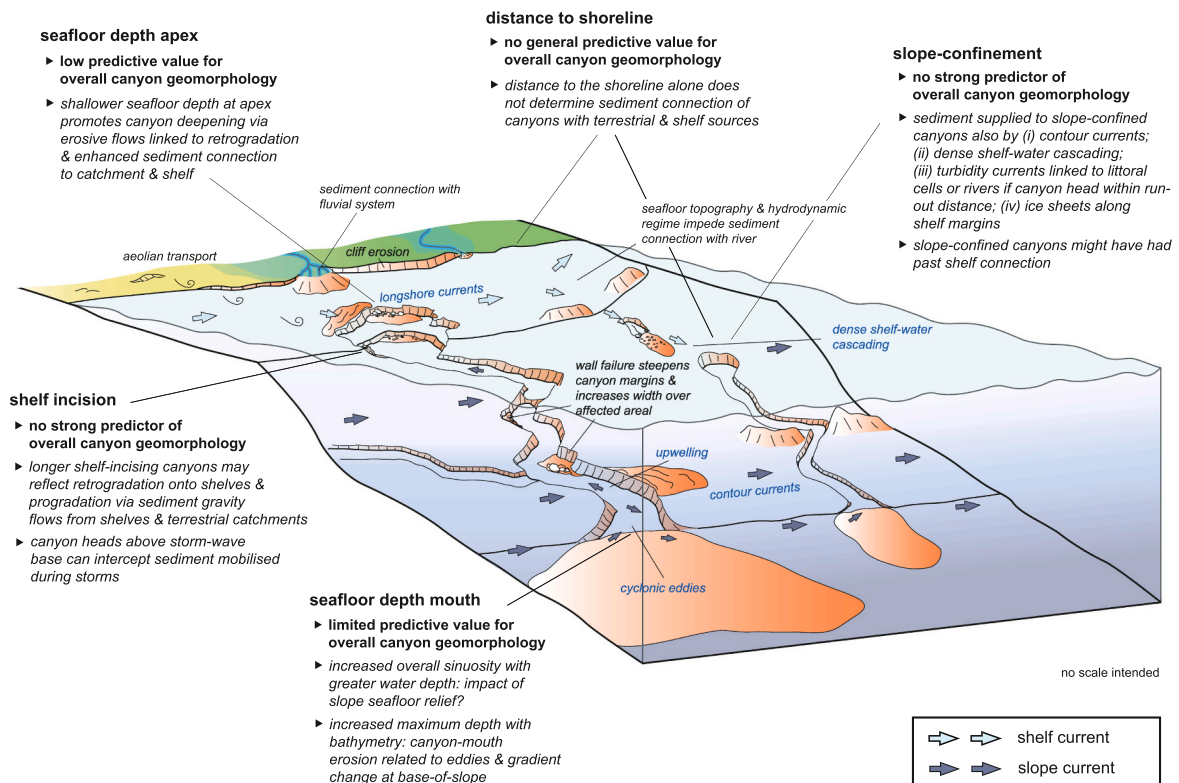


Fig. 24. a&b: Schematic diagrams summarising controlling factors of submarine-canyon geomorphology recognised in the literature and whose statistical signature has been evaluated in this study.

canyons are constrained by the interplay of canyon-margin failure and canyon-floor and canyon-margin aggradation by flows.

Our quantitative characterisation of how canyon morphometric parameters vary as a function of environmental factors demonstrates that the interplay of controls on canyon geomorphology is more complex than hitherto considered in canyon classification schemes (e.g. Jobe et al., 2011), numerical (e.g. Wan et al., 2021) and published conceptual models of canyon evolution (e.g. Chiang and Yu, 2006; Micallef et al., 2014), of deep-water systems and of source-to-sink (S2S) systems (e.g. Sømme et al., 2009; Nyberg et al., 2018). The predictive value of these models can be enhanced by considering the impact of the controlling factors identified in this study – including the hydrodynamic regime of oceans and seas, autogenic canyon processes, characteristics of continental margin physiography and the canyon physiographic setting.

The findings of this study might also aid in estimation of the original geometry of ancient canyons and channel forms whose infills are now preserved in subsurface and outcrop, and in the interpretation of their formative environments, particularly where information on the environmental setting, margin physiography and bathymetry are limited due to scarcity of data (e.g. Martinsen et al., 2010; Helland-Hansen et al., 2016; Xu et al., 2017).

Results of this work will aid analyses of source-to-sink systems, i.e., spanning fluvial, paralic and deep-water domains (e.g. Sømme et al., 2009; Nyberg et al., 2018; Wang et al., 2019), by illuminating the response of slope systems to controlling factors on sedimentary processes from terrestrial hinterlands to deep-water environments. Further research is needed to investigate the relative scaling between features of these clastic environments and those of submarine canyons, and of the relative influence of marine hydrodynamic processes on submarine-canyon geomorphology.

#### Declaration of Competing Interest

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

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