Title
Global distribution of coastal cliffs

Permalink
https://escholarship.org/uc/item/579326kr

Journal
Earth Surface Processes and Landforms, 44(6)

ISSN
0197-9337 1096-9837

Authors
Young, Adam P
Carilli, Jessica E

Publication Date
2019-01-30

DOI
10.1002/esp.4574

EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms (2019)

(wileyonlinelibrary.com) DOI: 10.1002/esp.4574

Global distribution of coastal cliffs

Adam P. Young* and **Jessica E. Carilli**[†]
Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0209, USA

Received 10 August 2018; Revised 17 December 2018; Accepted 20 December 2018

*Correspondence to: Adam Young, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Dr., La Jolla, CA, 92093-0209, USA. E-mail: adyoung@ucsd.edu
[†]Current address: Energy and Environmental Sciences, Space and Naval Warfare Systems Center Pacific, 53475 Strothe Rd, San Diego, CA 92152, USA

Earth Surface Processes and Landforms

ABSTRACT: Previous studies have estimated that coastal cliffs exist on about 80% of the global shoreline, but have not been validated on a global scale. This study uses two approaches to capture information on the worldwide existence and erosion of coastal cliffs: a detailed literature survey and imagery search, and a GIS-based global mapping analysis. The literature and imagery review show coastal cliffs exist in 93% of the combined recognized independent coastal states and non-independent coastal regions worldwide (total of 213 geographic units). Additionally, cliff retreat rates have been quantified in at least one location within 33% of independent coastal states and 15% of non-independent regions. The GIS-based mapping used the near-global Shuttle Radar Topography Mission 3 arc second digital elevation model and Arctic Coastal Dynamics Database to obtain near-global backshore coastal elevations at 1 km alongshore intervals comprising about 1,340,000 locations (81% of the world vector shoreline). Backshore coastal elevations were compared with the mapped distribution of European coastal cliffs to produce a model training set, and this relationship was extended globally to map the likelihood of coastal cliff locations. About 21% of the transects (17% of the world vector shoreline) were identified as mangroves and eliminated as potential cliff locations. The results were combined with estimates of cliff percentages for Greenland and Antarctica from the literature, extending the global coverage to estimate cliff occurrence across 89% of the world vector shoreline. The results suggest coastal cliffs likely exist on about 52% of the global shoreline. © 2018 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons Ltd.

KEYWORDS: coastal cliff; global; retreat rate; erosion

Introduction

Coastal cliffs are important geomorphological features because they (1) provide sediment to adjacent beaches (Carter *et al.,* 1990; Young and Ashford, 2006; Brooks and Spencer, 2010; Young *et al.,* 2010; Trenhaile, 2016), (2) provide habitat to plants and animals (Swartz, 1966; Goldsmith, 1975; Naylor *et al.,* 2012), (3) are global tourist destinations (i.e. Big Sur in USA, Bonifacio in France (Figure 1(a)), The Twelve Apostles in Australia (Figure 1(b)), White Cliffs of Dover in England, and Phang Nga Bay in Thailand), (4) can collapse causing injury and fatalities (Aucote *et al.,* 2010; Young, 2018), and (5) erode, frequently threatening coastal communities, infrastructure, and historical sites (Figure 1(c)) around the world. These problems are expected to worsen with increasing global sea levels and coastal populations (Gornitz, 1991; Dawson *et al.,* 2009; Heberger *et al.,* 2009; National Research Council, 2012; Brown *et al.,* 2014; IPCC, 2014).

Coastal cliffs are either fronted by a shore platform (sometimes covered with sediment) or plunge directly into the ocean (Trenhaile, 1987; Sunamura, 1992, 2015; Figure 1). The global distribution of coastal cliffs (and rock coasts) is widely cited as 80% from Emery and Kuhn (1982). However, as noted by Naylor *et al.* (2010) 'there has been little to no research to substantiate' this statistic. Mapping the distribution of coastal cliffs or rock coasts is complicated because various classification schemes are often qualitative and subjective. For example, rock coasts are often divided into 'soft' and 'hard' rock coasts, which could be considered to respectively correspond to 'bluffs' and 'cliffs.' In some cases, 'coastal mountains' are classified differently than 'low relief' cliffs or bluffs. The boundaries between these divisions are vague and often defined relative to a particular section of coast. Furthermore, some coasts such as those in southern California contain composite cliffs composed of both relatively 'soft' and 'hard' rock (Young *et al.,* 2009). In many studies the term 'rock coasts' implies that cliffs are present. This study does not make the distinction between the various classifications and refers to all these features as coastal cliffs (Figure 1). The common attribute of these geomorphic features is an abrupt change in elevation at the coast. This study used this common attribute and a near-global high resolution elevation dataset to map cross-shore coastal elevation change and thereby estimate the global extent of cliffed coasts. A global perspective that compiles previous studies that have mapped coastal cliffs and/or estimated cliff retreat rates is also presented.

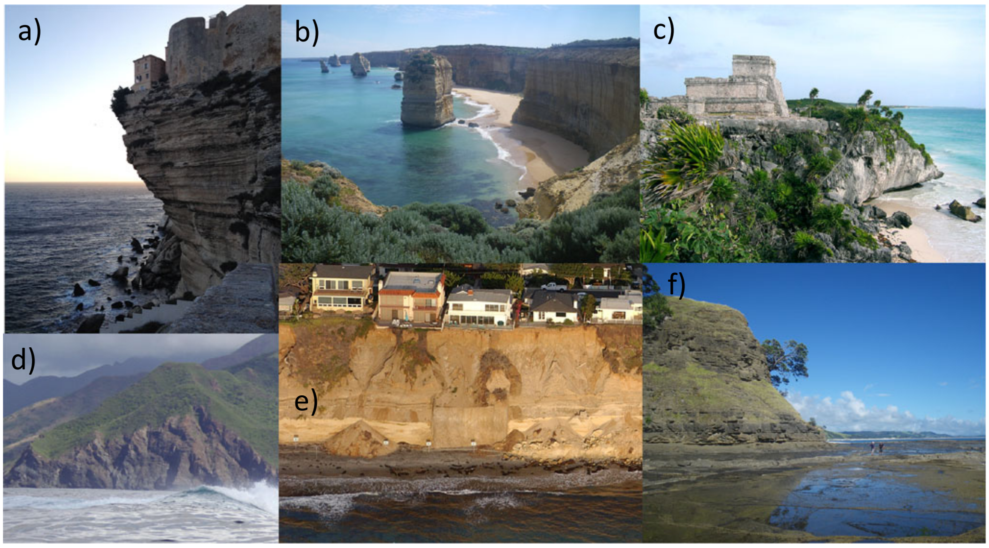


Figure 1. Examples of coastal cliffs and settings including (a) a village perched on top of limestone cliffs at Bonifacio, Corsica, France, (b) sea stacks and cliffs fronted by beaches at The Twelve Apostles, Victoria, Australia, (c) Mayan ruins on top of limestone cliffs at Tulum, Yucatan, Mexico, (d) plunging coastal cliffs and mountains at Parque Nacional Santa Rosa, Guanacaste, Costa Rica, (e) eroding sedimentary rock cliffs and cliff top development at Solana Beach, California, USA (photo: California Coastal Records Project, Kenneth and Gabrielle Adelman), and (f) a sedimentary rock cliff fronted by an extensive shore platform at Pakiri, New Zealand. [Colour figure can be viewed at wileyonlinelibrary.com]

Background

Several previous studies have mapped or provided regional estimates of coastal cliff distributions. The Eurosion project (Salman *et al.,* 2004) classified European coasts in a Geographic Information System (GIS) database and found that combined 'soft' and 'hard' rock categories comprise 47% of the coast. Hammar-Klose and Thieler (2001) provide GIS files of the 48 contiguous United States coastline where 'cliffed coasts, medium cliffs, low cliffs' comprise 41% of the coast. Other US studies estimate coastal cliff distribution at 72% in California (Griggs *et al.,* 2005), 50% in Maine (Hapke *et al.,* 2014), 58% in Oregon (Hapke *et al.,* 2014), and 32% in the Great Lakes (Mickelson *et al.,* 2004). Short and Woodroffe (2009) estimate 40% of the Australian coast is 'rocky'. Lantuit *et al.* (2012) found 35% of the Arctic coast is lithified (however this is not necessarily equivalent to cliffs). Examples of other regional studies with estimates of cliff or rocky coast distribution include: 60% for Japan (Sunamura *et al.,* 2014), 30% for Albania (Simeoni *et al.,* 1997), 29% for Colombia (Blanco-Chao *et al.,* 2014), 37% for South Korea (Choi and Seong, 2014) and 54% for Cuba (Anfuso *et al.,* 2017). In total, the amount of cliffed or rocky coastline has been estimated for 29 independent coastal states, Greenland, Antarctica, and the 48 contiguous United States (Figure 2(a), Supplementary Table I).

Previous global-scale maps of coastal landforms either present more broad categories, rather than specific features such as coastal cliffs, or were described as approximate (McGill, 1958). More recent digital global datasets such as DINAS-COAST (McFadden *et al.,* 2007; Vafeidis *et al.,* 2008) are based on previous work such as McGill (1958) and therefore still limited by those original datasets. Emery and Kuhn (1982) provide the only global map of coastal cliff distribution, which was based on the Morskoi Atlas (Isakov, 1953). However, the Emery and Kuhn (1982) map contains some known errors, such as neglecting the longest cliff line in the world, located along the Great Australia Bight (790 km; Short and Woodroffe, 2009), and classifying large portions of sandy shores along the Namib Desert coast in southwest Africa as cliffs.

Recently, Luijendijk *et al.* (2018) used satellite imagery and pixel-based supervised classification to conduct a global coastal analysis and estimated that 31% of ice free global shorelines are sandy. However, Luijendijk *et al.* (2018) does not consider backshore features such as coastal cliffs, and maps beaches backed by cliffs as 'sandy shorelines'. In another recent study, Prémaillon *et al.* (2018) used 58 publications to compile an extensive database of coastal cliff retreat rates from 16 different countries (mostly located in Europe, Oceania, and North America) totaling more than 1680 records.

This study builds upon previous work and provides the first high resolution near-global map showing the probability of coastal cliff occurrence, compiles information on the existence of coastal cliffs from the literature and photographic imagery from almost every coastal geographic region in the world, and compiles a global dataset of geographic regions in which cliff retreat rates have been documented in at least one location.

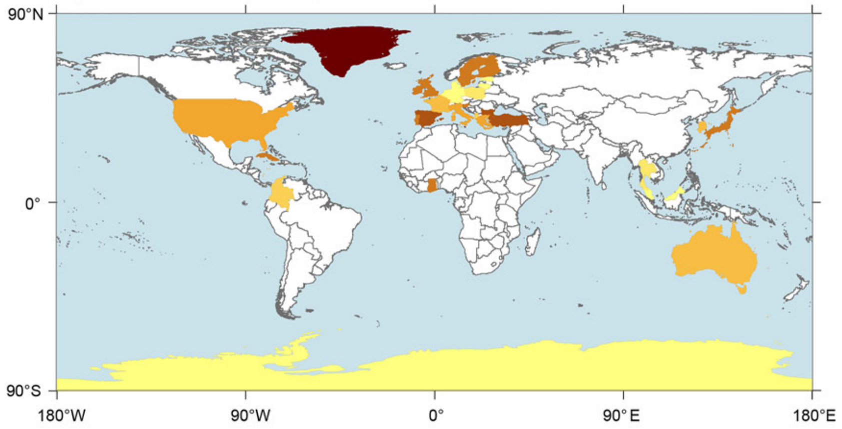
Methods

This study uses two approaches to capture information on the worldwide existence and erosion of coastal cliffs: a detailed literature survey and imagery search, and a GIS-based global mapping analysis.

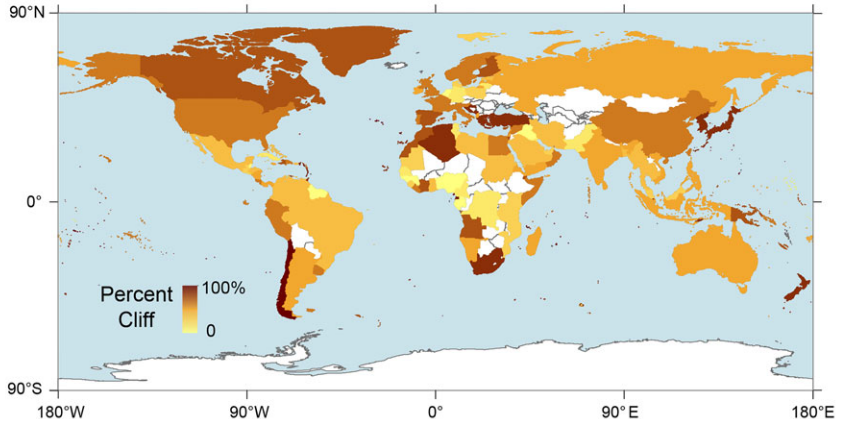
Literature and imagery assessment

This portion of the work was designed to determine whether every coastal nation (and/or affiliated areas: locations that are geographically distinct, but not independent states, such as Puerto Rico) around the world has cliffs along at least a portion of coastline. A search of the scientific literature was conducted, and references that discussed or contained photographic imagery showing coastal cliffs from each nation or geographic area were compiled. For those locations lacking evidence of coastal cliffs in the scientific literature, imagery uploaded by users to Google Earth (Version 7.1.8.3936) was explored to determine whether visual evidence of coastal cliffs was available for those regions.

The approximate length of coastline for each independent nation and/or affiliated geographic region was also searched



a) Previous Studies - Regional Percent Estimates of Coastal Cliffs



b) This Study - Regional Percent Estimates of Coastal Cliffs

Figure 2. Global map of regional coastal cliff percentage from (a) previous studies, and (b) this study. Regions are color coded by the percentage of cliffed coastline (yellow-brown). White land regions indicate either no data and/or inland regions. [Colour figure can be viewed at wileyonlinelibrary.com]

for in the literature. These values were primarily obtained from either the Central Intelligence Agency World Factbook (2013) or Burke *et al.* (2001), although other sources were used when these sources were insufficient. Coastline lengths were not available from any known sources for some islands or island groups, such as Bonaire and the US Minor Outlying Islands.

Additional literature searches were conducted to compile existing data on coastal cliff abundance (percentage of a given coastline comprised of cliffs) and cliff retreat rates. When average retreat rates or only single measured or estimated rates were given, these values were compiled; otherwise ranges of rates were compiled for this work. For geographic regions where many cliff retreat studies have been conducted (for example the United Kingdom and the United States), retreat rates were obtained from one regionally comprehensive source.

GIS global mapping methods

This study also combined the Shuttle Radar Topography Mission (SRTM) Water Body Dataset (https://lta.cr.usgs.gov/srtm_water_body_dataset) and Arctic Coastal Dynamics Database (ACDD) (Lantuit *et al.,* 2012) to develop a near-global dataset of backshore elevations at 1 km alongshore sample resolution. Combining these coastal elevation datasets provides coverage of 81% (SRTM = 75% and ACDD = 6%) of the World Vector Shoreline dataset (WVS) (Soluri and Woodson, 1990; Wessel and Smith, 1996).

The SRTM vector shoreline and associated SRTM 3 arc second (90 m) resolution digital elevation models (USGS, 2004), spanning latitudes 56° S to 60° N, cover 80% of Earth's landmass. The elevation data were collected in 2000 and have a reported vertical accuracy of 16 m, although Gorokhovich and Voustianiouk (2006) found better accuracies of 4–8 m. The SRTM vector shoreline was extracted from DTED Level 2.0 elevation data with ~30 m resolution, has estimated horizontal accuracy of 20 m with 90% confidence, and does not include small islands less than 300 m medial axis length (SRTM Water Body Data Product Specific Guidance, v.2.0, March 12, 2003). About 1,240,000 cross-shore transects were defined along the SRTM vector shoreline, spaced at 1 km intervals. Cross-shore orientation was defined as the average shoreline orientation over 1 km of shoreline centered on the transect location. The backshore elevation was defined as the maximum elevation (vertical datum EGM96) along each transect extending 100 m inland from the SRTM shoreline. Note that the backshore elevation is not always equivalent to cliff height unless the extended inland cliff top is flat.

The ACDD (Lantuit *et al.,* 2012) provides estimated backshore elevations for polygon segments covering about 100,000 km of the WVS in the Arctic, a region not covered by the SRTM. Each ACDD segment was spatially defined and assigned a single elevation by regional experts based on a variety of sources including local publications, gray literature, lidar data, and video footage (Lantuit H., personal communication June 12, 2017). The minimum and median shoreline segment lengths were 1 km and 38 km, respectively. For this study, the WVS was clipped with ACDD polygons, then sampled at

1 km alongshore intervals, and assigned the corresponding ACDD backshore elevation value. The Arctic database provided an additional ~100,000 cross-shore transects for a total of about 1,340,000 cross-shore transects (spaced at 1 km alongshore) for this study.

To determine the probability of coastal cliff existence at each of the global sample transect locations, a cliff probability curve was established using the mapped distribution of coastal cliffs from the Eurosion project (Salman *et al.,* 2004) and corresponding backshore transect elevation. For this study, these Eurosion classifications were considered coastal cliffs: classification A – 'Rocks and/or cliffs made of hard rock (little subject to erosion) with eventual presence of a rock platform'; classification B – 'Conglomerates and/or cliffs (example: chalk) i.e. subject to erosion: presence of rock waste and sediments (sand or pebbles) on the strand'; classification AC – 'Mainly rocky, little erodible, with pocket beaches (<200 m long) not localized'; and classification C – 'Small beaches (length of beach 200 to 1000 m) separated by rocky capes (<200 m long)'. All other categories were considered non-cliffed for this study. However, note that some scattered locations categorized by the Eurosion project as non-cliff such as 'harbors' and 'developed beaches' are backed by cliffs.

Each cross-shore transect was assigned a cliff or non-cliff classification, based on the closest Eurosion shoreline feature. Cross-shore transects greater than 100 m from a classified Eurosion shoreline feature, or where the shoreline features were unclassified, were neglected. The remaining approximately 51,000 transects were binned by backshore elevation using 1 m wide bins (transects were grouped by elevation in 1 m intervals). For each bin, the percentage of transects classified as cliffs by the Eurosion project was calculated and used to establish a relationship between transect backshore elevation and cliff percentage for a given elevation bin. Bins with less than 10 observations were removed and the remaining bins were used to develop a coastal cliff probability model based on the backshore transect elevation (Figure 3). The model compares well with bin data ($r^2 = 0.96$) and was used to identify a backshore elevation threshold of 4.4 m, above which the likelihood of cliffs existing exceeds 50%. This 4.4 m threshold represents the elevation in the Eurosion training dataset where transects were more likely classified as cliffs compared with other classifications.

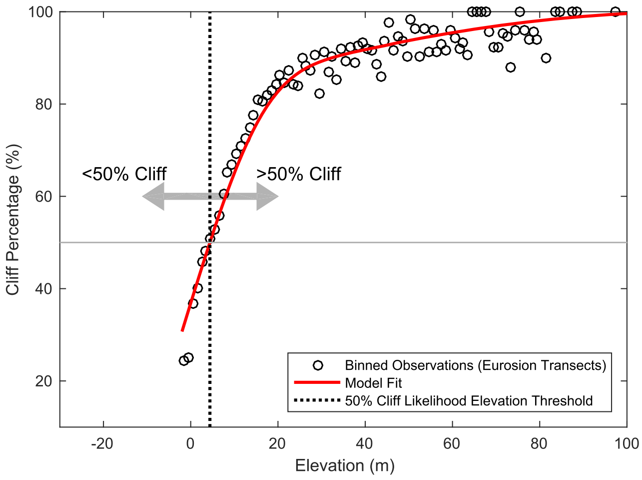


Figure 3. The relationship between binned (1 m wide intervals) observations of Europe's backshore coastal elevation and percentage of observations in each bin that are cliffed according to the Eurosion coastal geomorphic classification (Salman *et al.,* 2004). The binned observations were used to develop a model defining the relationship between backshore coastal elevation and probability of cliff existence for a given global coastal transect (red). The model fits well with the binned observations ($r^2 = 0.96$) and shows that transects with elevations >4.4 m are more likely (>50% chance) to contain coastal cliffs. [Colour figure can be viewed at wileyonlinelibrary.com]

The literature and imagery assessment (discussed in the Methods section) revealed 15 regions where cliffs do not exist. Transects in these regions in the global transect dataset were eliminated as potential cliff locations.

Mangroves could cause false-positive identification of coastal cliff features in this dataset. Mangroves grow in tropical and subtropical regions in the intertidal zone and range in height from 5 to 25 m (Simard *et al.,* 2008), greater than the 4.4 m threshold for cliff likelihood. Mangrove habitat is mostly confined to muddy coasts, where the trees grow between the land and sea, and therefore do not generally coexist with active coastal cliffs. Mangroves compose large sections of coast in Colombia (Blanco-Chao *et al.,* 2014), Malaysia (42% mangrove, Teh and Yap, 2010), Thailand (33% mangrove, Aksornkoae and Bird, 2010), and other regions. Giri *et al.* (2011) mapped the year 2000 global distribution of mangroves into a GIS polygon database, and found that mangroves occupied 137 760 km^2 of coastal habitat. Transects within 0.5 km of a mangrove polygon were also eliminated from the model developed here as potential cliff locations.

To quantify error, the automated global transect cliff classification system used here was compared with 850 manually classified locations along the California coast from Imperial Beach to the northern Big Sur Coast. This section of coast was selected because it contains a variety of coastal settings, including high relief natural cliffs, low relief developed cliffs, beaches backed by dunes, urbanized beaches, river mouths, and other features. The cliff classification model was not applied at transects identified as mangroves and therefore no model error assessment is needed for the classification.

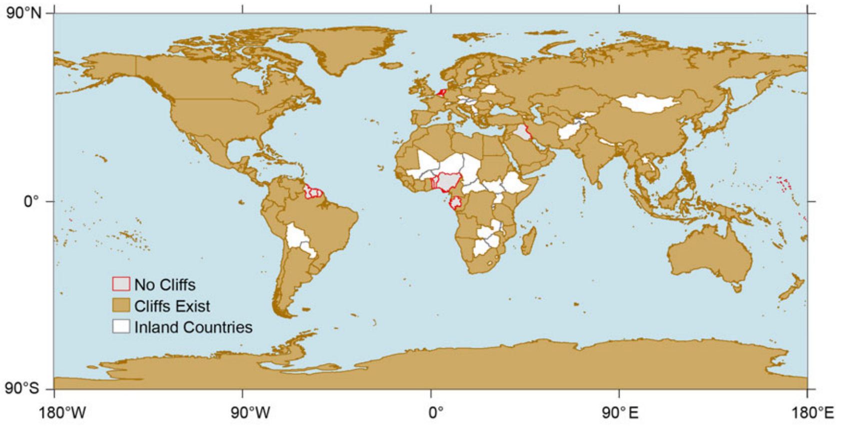
Results

Literature and imagery assessment results

Coastal cliffs exist in at least 142 (Figure 4(a), Supplementary Table I), or 92%, of the 154 currently US-recognized independent states of the world (https://www.state.gov/s/inr/rls/4250.htm) with coastlines (Burke *et al.,* 2001; Central Intelligence Agency, 2013). Cliffs also exist in 95% of other regions that are not officially independent states but are geographically distinct (Figure 4(a), Supplementary Table I, total 59 regions) such as Antarctica and Greenland (Bird, 2010; Hansom *et al.,* 2014). Combined, 93% of the total 213 geographic regions contain coastal cliffs on at least part of the shoreline. Recognized independent states without cliffs documented (to our knowledge) include: Belgium, Benin, Gabon, Guyana, Iraq, Marshall Islands, Nauru, Netherlands, Nigeria, Suriname, Togo, and Tuvalu. Non-independent regions without documented cliffs include French Guiana, Juan De Nova Island, and Tokelau (Supplementary Table I).

Sunamura (1992) compiled studies of cliff retreat located in 16 different independent states, and Moses (2013) provides a summary of additional cliff retreat rates in tropical independent states and several territories. More recently, Prémaillon *et al.* (2018) compiled cliff retreat rates from many regions worldwide. Numerous additional cliff retreat studies have been conducted recently for individual nations, regions, or sites. In total, coastal cliff retreat rates from at least one site have now been documented in at least 50 (33%) of the 154 independent states (Figure 4(b), Supplementary Table II), nine (15%) of the non-

a) Regions with Documented Coastal Cliffs



b) Regions with Documented Coastal Cliff Retreat Rates

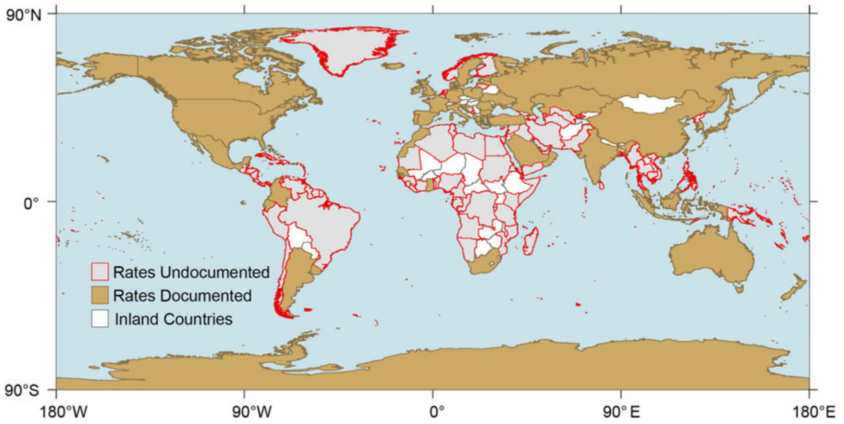


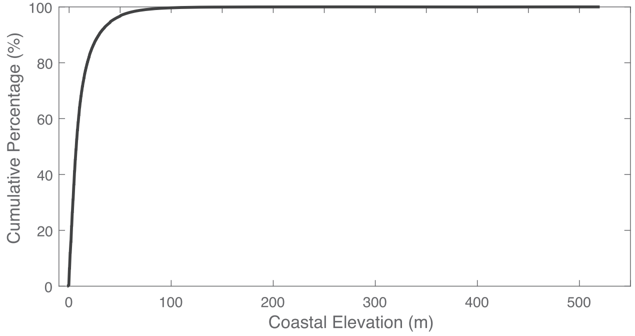
Figure 4. Global map of regions where (a) cliffs exist (brown) or do not (red outline), and (b) coastal cliff retreat rates have been quantified in at least one location (brown), or have not been quantified (red outline). In both (a) and (b), white land areas indicate inland countries. [Colour figure can be viewed at wileyonlinelibrary.com]

independent regions, and 59 (28%) of the total 213 global regions. These retreat rates vary widely, from essentially no detectable erosion to many meters of retreat per year.

GIS global mapping results

Global backshore elevations ranged from 0 m to >500 m with an average and standard deviation of 12.0 m and 15.4 m, respectively (Figure 5(a)). The distribution of backshore transect elevations is concentrated at lower elevations with 90% of coastal regions averaging less than 30 m in elevation (Figure 5(a)). The highest elevations (>500 m) within the SRTM and ACDD datasets were located in Yemen and British Columbia, Canada; however taller cliffs outside the study area are known to exist, such as ‘Thumbnail’ seacliff in southern Greenland at ~1500 m in elevation (Google Earth, 2017). About 21% of the transects (17% of the world vector shoreline) were identified as mangroves and eliminated as potential cliff locations. The results suggest that about 51% of the near global transects are likely cliffed (>50% chance) and 22% are very likely (>75% chance) cliffed (Figure 5(b)). Figure 6 shows the mapped distribution of coastal cliff likelihood. Importantly, this map and results present the likelihood of transects containing cliffs and are best interpreted regionally; they do not present the definitive locations of coastal cliffs worldwide. Using a 10 m threshold, 37% of global transects are likely to contain cliffs (with high confidence level). Combined with estimates

a) Cumulative Percentage of Backshore Coastal Elevation



b) Cumulative Percentage of Coastal Cliff Likelihood

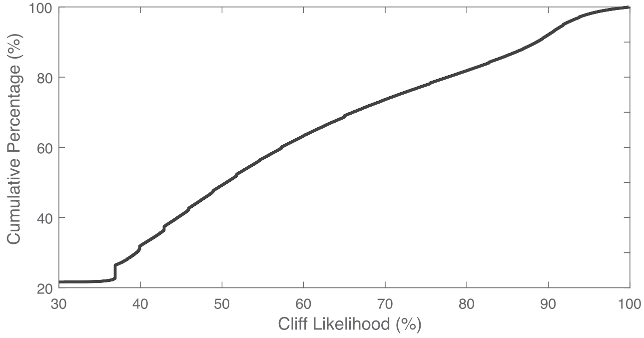


Figure 5. Cumulative percentage of (a) global backshore transect elevations and (b) transect cliff likelihood.

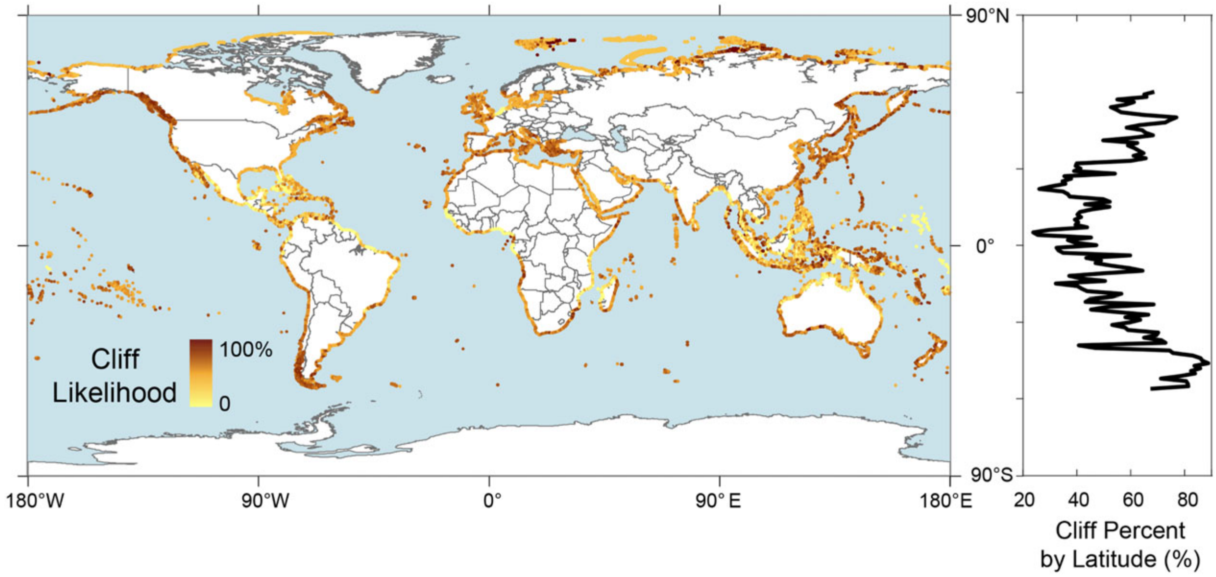


Figure 6. Global map (left panel) of cliff likelihood (data thinned to present the average of all transects within a 50 km radius for display purposes), and (right panel) relationship between latitude and global cliff distribution. [Colour figure can be viewed at wileyonlinelibrary.com]

of cliff percentages for Greenland and Antarctica from the literature, extending the coverage to 89% of the world vector shoreline, about 52% of the coast is likely cliffed (>50% chance).

Coastal cliffs are more common at mid-latitudes compared with tropical low latitudes in both hemispheres (Figure 6). The general latitudinal trend is similar to beach distributions (Luijendijk *et al.,* 2018) except cliffs and beach maxima are at 45–50° and 25–30°, respectively. Abundant coastal mangroves (Giri *et al.,* 2011) limit beach (Luijendijk *et al.,* 2018) and coastal cliff occurrences in the humid tropics. This study lacks complete high latitude elevation data needed for high latitude cliff distribution analysis.

Error assessment

In the California test section, incorrect classifications mostly occurred where beaches were classified as cliffs; these misclassifications were concentrated at coastal sections with elevations of 4–9 m (Figure 7). Incorrectly classified locations were often spatially grouped, occurring along beaches backed by large dunes (i.e. Oceano) and heavily urbanized beaches with large coastal structures (e.g. Los Angeles). Errors from cliffs incorrectly classified as beaches often occurred at locations where the transect did not intersect land because of inconsistencies between the SRTM vector shoreline and SRTM digital elevation model land boundary. Other errors occurred at locations with highly irregular (non-linear) shorelines such as rock promontories where the transect did not intersect the main land mass. Portions of these classification errors cancel each other out such that the total error was 14%. Errors in the California test section decrease from 14% to 4% misclassifications for elevations of 10 m or more. The errors in the California test section are consistent with the model fit (Figure 3), where more classification uncertainty occurs at lower elevations (3–8 m) around the 50% cliff likelihood level.

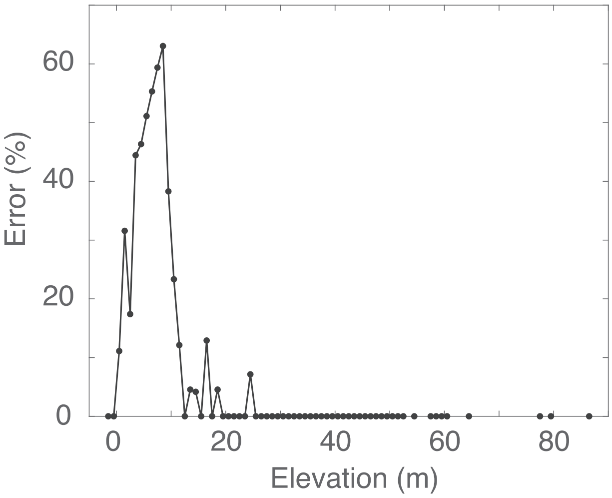


Figure 7. Transect classification error versus transect backshore elevation in the 850 km California test section.

Discussion

Overall, the results suggest the global percentage of cliffed coasts is less than Emery and Kuhn's (1982) estimate of 80%. In California, the results suggest that 67% of the coastline is likely comprised of cliffs (> 50% chance), consistent with the Griggs *et al.* (2005) estimate of 72%. In addition, about 46% of Australia transects were classified as likely cliffs, similar to a previous estimate of 40% (Short and Woodroffe, 2009). Further similar estimates of coastal cliff abundance from the literature compared with this study (Supplementary Table I) occurred in Albania (previous 30%, here 47%), Colombia (previous 29%, here 33%), Cuba (previous 14%, here 12%), Ghana (previous 53%, here 40%), Japan (previous 60%, here 72%), Malta (previous 88%, here 87%), Poland (previous 17%, here 29%), Portugal (previous 51%, here 53%), Turkey (previous 69%, here 74%), and the contiguous 48 USA states (previous 41%, here 37%).

Poor agreement between previous research and this study occurred in South Korea (previous 37%, here 75%; Supplementary Table I). Human activities and land reclamation in South Korea have converted 51% (Choi and Seong, 2014) of the coast from natural landforms to artificial, and probably generated large disparity in cliff percentage estimates because the present methods cannot distinguish between natural and artificial coastal features. Excluding South Korea, the mean absolute difference between previous estimates and the modeled regions of cliff percentage is 10% (difference ranging from –28% to 26%).

Other differences between this study and previous studies could occur because coastline length varies with scale. Using small-scale maps with limited detail decreases coastal length measurements (Wessel and Smith, 1996). This could cause studies using small-scale maps to measure less coastal cliff coverage compared with studies using large-scale maps, as cliffs and rocky shores tend to have relatively more complex planimetric alongshore lengths compared with sandy shorelines.

This study used a systematic method to quantify coastal cliff existence and generate the first high resolution map of global cliff distribution. The results confirm the presence of coastal cliffs in almost all regions of the world. The global presence of eroding coastal cliffs, combined with increasing global coastal populations and sea levels, suggests that problems associated with cliffs such as coastal landslides and infrastructure damage will increasingly pose coastal hazards and management issues around the world.

Further research to improve this work could include using new higher resolution global and near-global elevation models such as the 1 Arc second STRM model (lta.cr.usgs.gov/SRTM1Arc) and TanDEM X (Zink *et al.,* 2014). Global void-free versions of these models were not available at the time of data processing and thus deemed unsuitable for this study.

Conclusion

A literature and imagery review showed that coastal cliffs exist in 93% of the combined recognized independent coastal states and non-independent coastal regions worldwide. Cliff retreat rates have been quantified in at least one location within 33% of independent coastal states and 15% of non-independent regions. A near-global elevation dataset was used to obtain backshore coastal elevations at 1 km alongshore intervals at ~1,340,000 global locations (81% of the world vector shoreline) and compared with the mapped distribution of European coastal cliffs to produce a GIS-based model training set. The model was extended globally to map the likelihood of coastal cliff locations and to generate the first high resolution map of global cliff distribution. The results were combined with estimates of cliff percentages for Greenland and Antarctica from the literature, extending the coverage to 89% of the world vector shoreline. The results suggest coastal cliffs likely exist on about 52% of the global shoreline.

Acknowledgements—APY was funded by the California Department of Parks and Recreation, Division of Boating and Waterways (DPR-DBW) with the University of California. We thank V. Regard and one anonymous reviewer for constructive comments that significantly improved this manuscript. We also thank M. Dickson for thoughtful and helpful discussions regarding this manuscript.

References

Aksornkoae A, Bird E. 2010. Thailand Andaman Sea Coast. In *Encyclopedia of the World's Coastal Landforms*, Bird E (ed). Springer Science & Business Media: Dordrecht; 1113–1116.

Anfuso G, Williams AT, Martínez GC, Botero CM, Hernández JC, Pranzini E. 2017. Evaluation of the scenic value of 100 beaches in Cuba: implications for coastal tourism management. *Ocean and Coastal Management* **142**: 173–185. https://doi.org/10.1016/j.ocecoaman.2017.03.029.

Aucote HM, Miner A, Dahlhaus P. 2010. Rockfalls: predicting high-risk behaviour from beliefs. *Disaster Prevention and Management: An International Journal* **19**: 20–31. https://doi.org/10.1108/09653561011022117.

Bird E. 2010. Greenland. In *Encyclopedia of the World's Coastal Landforms*, Bird E (ed). Springer Science & Business Media: Dordrecht; 319–321.

Blanco-Chao R, Pedoja K, Witt C, Martinod J, Husson L, Regard V, Audin L, Nexer M, Delcaillau B, Saillard M, Melnick D. 2014. The rock coast of South and Central America. *Geological Society, London, Memoirs* **40**: 155–191. https://doi.org/10.1144/M40.10.

Brooks SM, Spencer T. 2010. Temporal and spatial variations in recession rates and sediment release from soft rock cliffs, Suffolk coast, UK. *Geomorphology* **124**: 26–41. https://doi.org/10.1016/j.geomorph.2010.08.005.

Brown S, Nicholls RJ, Hanson S, Brundrit G, Dearing JA, Dickson ME, Gallop SL, Gao S, Haigh ID, Hinkel J, Jiménez JA. 2014. Shifting perspectives on coastal impacts and adaptation. *Nature Climate Change* **4**: 752. https://doi.org/10.1038/nclimate2344.

Burke L, Kura Y, Kassem K, Revenga C, Spalding M, McAllister D, Caddy J. 2001. *Coastal Ecosystems*. World Resources Institute: Washington, DC.

Carter RWG, Jennings SC, Orford JD. 1990. Headland erosion by waves. *Journal of Coastal Research* **6**: 517–529.

Central Intelligence Agency (CIA). 2013. *The World Factbook 2013-14*. CIA: Washington, DC.

Choi KH, Seong YB. 2014. The rock coast of Korea. *Geological Society, London, Memoirs* **40**: 193–202. https://doi.org/10.1144/M40.11.

Dawson RJ, Dickson ME, Nicholls RJ, Hall JW, Walkden MJ, Stansby PK, Mokrech M, Richards J, Zhou J, Milligan J, Jordan A. 2009. Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. *Climatic Change* **95**: 249–288. https://doi.org/10.1007/s10584-008-9532-8.

Emery KO, Kuhn GG. 1982. Sea cliffs: their processes, profiles, and classification. *Geological Society of America Bulletin* **93**: 644–654. https://doi.org/10.1130/0016-7606(1982)93<644:SCTPPA>2.0.CO;2.

Giri C, Ochieng E, Tieszen LL, Zhu Z, Singh A, Loveland T, Masek J, Duke N. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography* **20**: 154–159. https://doi.org/10.1111/j.1466-8238.2010.00584.x.

Goldsmith FB. 1975. The sea-cliff vegetation of Shetland. *Journal of Biogeography* **2**: 297–308. https://doi.org/10.2307/3038003.

Google Earth, Version 7.1.8.3936.2017. Thumbnail Cliff, Latitude 60.110029, Longitude -44.498041, Image date 9/9/2015, Accessed 6/12/2017.

Gornitz V. 1991. Global coastal hazards from future sea level rise. *Global and Planetary Change* **3**: 379–398. https://doi.org/10.1016/0921-8181(91)90118-G.

Gorokhovich Y, Voustianiouk A. 2006. Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics. *Remote Sensing of Environment* **104**: 409–415. https://doi.org/10.1016/j.rse.2006.05.012.

Griggs GB, Patsch K, Savoy LE. 2005. *Living with the Changing California Coast*. University of California Press: Berkeley, CA.

Hammar-Klose ES, Thieler ER. 2001. *Coastal vulnerability to sea-level rise: A preliminary database for the U.S. Atlantic, Pacific and Gulf of Mexico coasts [CD-ROM]*, Vol. **68**. US Geological Survey Digital Data Service: Woods Hole MA. https://doi.org/10.3133/ds68.

Hansom JD, Forbes DL, Etienne S. 2014. The rock coasts of polar and sub-polar regions. *Geological Society, London, Memoirs* **40**: 263–281. https://doi.org/10.1144/M40.16.

Hapke CJ, Adams PN, Allan J, Ashton A, Griggs GB, Hampton MA, Kelly J, Young AP. 2014. The rock coast of the USA. *Geological Society, London, Memoirs* **40**: 137–154. https://doi.org/10.1144/M40.9.

Heberger M, Cooley H, Herrera P, Gleick H, Moore E. 2009. The Impacts of Sea-Level Rise on the California Coast. In *CEC-500-2009-024-F*. Institute: Pacific.

IPCC. 2014. Climate Change 2014: Synthesis Report. In *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Core Writing Team, Pachauri RK, Meyer LA (eds). Intergovernmental Panel on Climate Change: Geneva, Switzerland 10013/epic.45156.d001.

Isakov IS. 1953. *Morskoi Atlas*. Ministry of the Navy of the U.S.S.R: Moscow Volume 2, Plate 13.

Lantuit H, Overduin PP, Couture N, Wetterich S, Aré F, Atkinson D, Brown J, Cherkashov G, Drozdov D, Forbes DL, Graves-Gaylord A. 2012. The Arctic coastal dynamics database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts* **35**: 383–400. https://doi.org/10.1007/s12237-010-9362-6.

Luijendijk A, Hagenaars G, Ranasinghe R, Baart F, Donchyts G, Aarninkhof S. 2018. The State of the World's Beaches. *Scientific Reports* **8**: 6641. https://doi.org/10.1038/s41598-018-24630-6.

McFadden L, Nicholls RJ, Vafeidis A, Tol RS. 2007. A methodology for modeling coastal space for global assessment. *Journal of Coastal Research* **23**: 911–920. https://doi.org/10.2112/04-0365.1.

McGill JT. 1958. Map of coastal landforms of the world. *Geographical Review* **43**: 402–405. https://doi.org/10.2307/212259.

Mickelson DM, Edil TB, Guy DE. 2004. Erosion of coastal bluffs in the Great Lakes. In *Formation, Evolution, and Stability of Coastal Cliffs—Status and Trends*, Hampton MA, Griggs GB (eds), Vol. **1683**. USGS Professional Paper; 107–123.

Moses CA. 2013. Tropical rock coasts: cliff, notch and platform erosion dynamics. *Progress in Physical Geography* **37**: 206–226. https://doi.org/10.1177/0309133312460073.

National Research Council. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. The National Academy Press: Washington DC. https://doi.org/10.17226/13389.

Naylor LA, Coombes MA, Viles HA. 2012. Reconceptualising the role of organisms in the erosion of rock coasts: a new model. *Geomorphology* **157**: 17–30. https://doi.org/10.1016/j.geomorph.2011.07.015.

Naylor LA, Stephenson WJ, Trenhaile AS. 2010. Rock coast geomorphology: recent advances and future research directions. *Geomorphology* **114**: 3–11. https://doi.org/10.1016/j.geomorph.2009.02.004.

Prémaillon M, Regard V, Dewez TJ, Auda Y. 2018. GlobR2C2 (Global Recession Rates of Coastal Cliffs): a global relational database to investigate coastal rocky cliff erosion rate variations. *Earth Surface Dynamics* **6**: 651–668. https://doi.org/10.5194/esurf-6-651-2018.

Salman A, Lombardo S, Doody P. 2004. Living with coastal erosion in Europe: sediment and space for sustainability. *Eurosion project reports*. Office for Official Publications of the European Communities. http://resolver.tudelft.nl/uuid:483327a3-dcf7-4bd0-a986-21d9c8ec274e

Short AD, Woodroffe CD. 2009. *The Coast of Australia*. Cambridge University Press: Melbourne, Australia.

Simard M, Rivera-Monroy VH, Mancera-Pineda JE, Castañeda-Moya E, Twilley RR. 2008. A systematic method for 3D mapping of mangrove forests based on Shuttle Radar Topography Mission elevation data, ICEsat/GLAS waveforms and field data: application to Ciénaga Grande de Santa Marta, Colombia. *Remote Sensing of Environment* **112**: 2131–2144. https://doi.org/10.1016/j.rse.2007.10.012.

Simeoni U, Pano N, Ciavola P. 1997. The coastline of Albania: morphology, evolution and coastal management issues. *Bulletin-Institut Oceanographique Monaco-Numero spécial* **18**: 151–168.

Soluri EA, Woodson VA. 1990. World vector shoreline. *The International Hydrographic Review* **67**: 27–35.

Sunamura T. 1992. *Geomorphology of Rocky Coasts*. John Wiley & Sons: Chichester.

Sunamura T. 2015. Rocky coast processes: with special reference to the recession of soft rock cliffs. *Proceedings of the Japan Academy, Series B* **91**: 481–500. https://doi.org/10.2183/pjab.91.481.

Sunamura T, Tsujimoto H, Aoki H. 2014. The rock coast of Japan. *Geological Society, London, Memoirs* **40**: 203–223. https://doi.org/10.1144/M40.12.

Swartz LG. 1966. Sea-cliff birds. In *Environment of the Cape Thompson region, Alaska*, Wilimovsky NJ, Wolfe JN (eds). US Atomic Energy Commission: Oak Ridge. TN PNE-**481**; 611–678.

Teh TS, Yap HB. 2010. Malaysia. In *Encyclopedia of the World's Coastal Landforms*, Bird E (ed). Springer Science & Business Media: Dordrecht.

Trenhaile A. 2016. Rocky coasts⍰their role as depositional environments. *Earth-Science Reviews* **159**: 1–13. https://doi.org/10.1016/j.earscirev.2016.05.001.

Trenhaile AS. 1987. *The Geomorphology of Rock Coasts*. Oxford University Press: New York.

USGS. 2004. *Shuttle Radar Topography Mission, 3 Arc Second, Filled Finished 3.0*. Global Land Cover Facility, University of Maryland, College Park: Maryland February 2000.

Vafeidis AT, Nicholls RJ, McFadden L, Tol RS, Hinkel J, Spencer T, Grashoff PS, Boot G, Klein RJ. 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise. *Journal of Coastal Research* **24**: 917–924. https://doi.org/10.2112/06-0725.1.

Wessel P, Smith WHF. 1996. A global self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research* **101**: 8741–8743. https://doi.org/10.1029/96JB00104.

Young AP. 2018. Decadal-scale coastal cliff retreat in southern and central California. *Geomorphology* **300**: 164–175. https://doi.org/10.1016/j.geomorph.2017.10.010.

Young AP, Ashford SA. 2006. Application of airborne LIDAR for seacliff volumetric change and beach-sediment budget contributions. *Journal of Coastal Research* **22**: 307–318. https://doi.org/10.2112/05-0548.1.

Young AP, Guza RT, Flick RE, O'Reilly WC, Gutierrez R. 2009. Rain, waves, and short-term evolution of composite seacliffs in southern California. *Marine Geology* **267**: 1–7. https://doi.org/10.1016/j.margeo.2009.08.008.

Young AP, Raymond JH, Sorenson J, Johnstone EA, Driscoll NW, Flick RE, Guza RT. 2010. Coarse sediment yields from seacliff erosion in the Oceanside littoral cell. *Journal of Coastal Research* **26**: 580–585. https://doi.org/10.2112/08-1179.1.

Zink M, Bachmann M, Brautigam B, Fritz T, Hajnsek I, Moreira A, Wessel B, Krieger G. 2014. TanDEM-X: the new global DEM takes shape. *IEEE Geoscience and Remote Sensing Magazine* **2**: 8–23. https://doi.org/10.1109/MGRS.2014.2318895.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1 References. Supporting information
Table S1. Supporting information
Table S2. Supporting information
Table S1 and S2 Metadata. Supporting information