GlobR2C2 (Global Recession Rates of Coastal Cliffs): a global relational database to investigate coastal rocky cliff erosion rates variations.

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Abstract.

Rocky coast erosion (i.e. cliff retreat) is caused by a complex interaction of various forcings that could be marine, subaerial or due to rock mass properties. From Sunamura's seminal work in 1992, it is known that cliff retreat rates are highly variable over at least four orders of magnitude at least, from 1 $\mathrm{mm.yr^{-1}}$ to 10 $\mathrm{m.yr^{-1}}$. While numerous local studies exist and explain erosion processes on specific sites, there is a lack at the global scale. In order to quantify and rank the various parameters influencing erosion rates, we compiled existing local studies in a global database called GlobR2C2 (for Global Recession Rates of Coastal Cliffs). This database reports erosion rates from publications, cliff setting and measurement specifications; it is compiled from peer reviewed articles and national databases. In order to be homogeneous, marine and climatic forcings were recorded from global models and reanalysis. Currently, GlobR2C2 contains 58 publications which represents 1530 cliffs studied and more than 1680 erosion rate estimates. A statistical analysis was conducted on this database to explore links between erosion rate and forcings at global scale. Rock resistance, inferred through Hoek and Brown (1997) criterion, is the strongest signal explaining variation in erosion rate. Median erosion rates are of 2.9 $\mathrm{cm.yr^{-1}}$ for hard rocks, 10 $\mathrm{cm.yr^{-1}}$ for medium rocks and 23 $\mathrm{cm.yr^{-1}}$ for weak rocks. Concerning climate, only the number of frost days (number of day per year below 0°C) for weak rocks shows a significant, positive, trend with erosion rate. The other climatic and marine forcings do not show any clear and significant relationship with cliff retreat rate. In this first version, GlobR2C2, with its current encompassing vision, has broad implications. Critical knowledge gaps have come to light and prompt a new coastal rocky shore research agenda. Further study of these questions is paramount if one day we hope to answer such questions as coastal rocky shore response to sea-level rise or to increased storminess.

1 Introduction

Rock coasts are characterized by dynamically linked cliff retreat and shore platform erosion (Moses and Robinson, 2011). By comparison between continental and coastal cliffs, it is clear that the presence of the sea is a fundamental driver of cliff retreat (Fig.1). But, as Moses and Robinson (2011) posit, "our understanding of their dynamics and our ability to predict their evolution over time remains severely limited". Kennedy (2014) emphasizes the growing number of quantitative studies, spurred by the development of new methods like lidar techniques. According to their analysis, a reassessment of cliff retreat rates is needed. Hence, the purpose of this paper is to take advantage of this growing corpus of data in order to quantitatively analyse cliff erosion drivers.

These drivers can be divided in three groups, depending on their nature (Fig.2). The first group of drivers concerns marine forcings. Waves attack and weaken cliff base, sometimes carving a notch, leading to cliff instability and subsequent collapse (e.g. Benumof et al., 2000; Caplain et al., 2011). It is a common assumption in coastal landscape evolution model and leads to the development of a shore platform below the cliff. It has sometimes been described as entirely shaped by the waves, leading to the dabated term of "wave cut platform" (e.g. Anderson et al., 1999). The reality is more complex (see thereafter); we prefer the term of "(rock) shore platform". Debris aprons are removed by sea action, allowing for renewed wave attack at cliff base. Cliff base weakening, cliff collapse and debris apron removal, before renewed cliff-base weakening can be called platform/cliff erosion cycle (e.g. Caplain et al., 2011). Wave assailing force depends on wave energy dissipation over the shore platform (e.g. Sunamura, 1992; Trenhaile, 2000). The wider and shallower the platform is, the lower is the remaining wave power at cliff foot. Hence platforms can be regarded as natural defences against wave attack to the cliff. The shore platform evolves under marine forcing like wave agitation and associated shear stress (e.g. Sallenger Jr et al., 2002; Stephenson and Kirk, 2000; Sunamura, 1992; Trenhaile, 2008, 2009), or tide-induced wetting and drying cycles (Kanyaya and Trenhaile, 2005; Stephenson and Kirk, 2000). The second group of drivers is rock mass properties that are believed to have a strong influence on cliff evolution (Mortimore and Duperret, 2004). The rock mass behaviour depends on its lithology, structure, fracturing and weathering (e.g. Cruslock et al., 2010). The third group of drivers is made of subaerial processes. Climate through precipitation, temperature or frost occurrences (e.g. Dewez et al., 2015) may either provoke cliff instability or prepare for it by physical and chemical weathering (Duperret et al., 2005).

Each of these have been proven to be efficient in their own way in cliff retreat phenomena, but their relative importance is perceived differently across studies (Fig.2), likely due to the small spatial extent of the sites or the authors' field of expertise. Some attempts exist at the local scale to rank the different drivers (e.g. Earlie et al., 2015; Lim et al., 2010) but these hierarchies can hardly be upscaled.

Some studies aim at quantifying cliff retreat rates at the regional scale, i.e., coastal sections of several tens to hundreds of kilometres. Those studies often pertain to risk management (Gibb, 1978; Hapke et al., 2009) or otherwise they are focused on a certain type of rock to understand its impact on cliff dynamics (Moses and Robinson, 2011). This implies that those studies cannot be used to describe global retreat drivers because : (i) they do not analyse the contribution of each driver, (ii) they remain too local and characterise a narrow range of forcings (e.g. climate, homogeneous lithology . . .)

In order to overcome biases inherent to individual approaches, studies at global scale have been conducted. They are often based on morphometry. For example, the classic study of Emery and Kuhn (1982) interprets cliff profile morphology as a function of cliff top and toe composition and marine and subaerial relative process efficiency. The only global, quantitative, data set was produced bySunamura (1992), on the basis of quantitative studies published prior to that date. Sunamura's database was only used by Woodroffe (2002) to evaluate ranges of erosion rates for different lithologic type. Up to now, those rates have never been related to environmental factors.

Since Sunamura's 1992 compilation, 26 years ago, many new quantitative studies have been published. They took advantage of several technological changes in that time interval. National mapping agencies released their aerial photography archives online, allowing researchers to record cliff top retreat over decades. These provide contemporary surveys with historical context. Airborne and terrestrial lidar as well as structure-from-motion (SfM) have revolutionized ad hoc surveys in the geosciences, making precise geometric information available where and when required. These methods enable the documentation of rockfalls from cliff face and assessments of their volumes. Software developments afforded massive 3D processing capabilities, even to non-specialists. So quantitative site studies are now addressing cliff face erosion style at the centimetre-scale (e.g. Dewez et al., 2013; Earlie et al., 2015; Gulayev and Buckeridge, 2004; Letortu et al., 2015; Rosser et al., 2007; Young and Ashford, 2006). This high spatial accuracy is nowadays added to high time resolution up to 20 minutes with detection of decimetric fragments from cliff face (Williams et al., 2018). Cliff recession phenomena have never been so well defined in space and time. It is now time to sort through possible processes generating cliff responses.

We updated Sunamura (1992)'s data set into the new database GlobR2C2, for Global Recession Rates of Coastal Cliffs, by taking advantage of all the existing site and regional studies and built a worldwide cliff recession database. This database is used in a new approach to link documented erosion rates and external forcings. It allows also to look for a relative efficiency of forcings relative to one another to explain erosion rates variations at the global scale. The benefits of this global approach is to erase local specificity and to seek for at global trends. The links between cliff retreat and environmental parameters were explored statistically. The synthetic database approach however is limited in that it compiles the information available for all studies at once. In that sense, it reduces information to the largest common denominator. The main goals of this paper are therefore to: (i) make a review of online literature in English, French or Spanish language from peer-reviewed or national databases providing cliff retreat rates; (ii) link a dependent variable: erosion rate to independent variables: cliff and meteo-marine settings. The analysis demonstrates the predominance of factors leading to cliff retreat.

2 Method

2.1 Study design

The main goal of this study is to link cliff retreat rate to external forcings at global scale. Those data exist in peer reviewed journal articles and national databases. Peer reviewed articles were chosen to be the source of cliff description and erosion rate value and settings. However, marine and continental forcings conditions are often reported in a very heterogeneous fashion. This information can either be completely lacking, incomplete or described in inconsistant ways. To overcome this issue, external global databases were used to harmonize forcings (i.e. tidal range, swell height, rainfalls etc. see sections 2.3.6 to 2.3.9). They provide standardized and reputable information for cliff height, sea condition and atmospheric climate.

The different steps of the study described in subsequent paragraphs are: (i) design and filling of a relationaldatabase with raw data, (ii) post-processing on database fields in order to tidy up the data (iii) statistical exploration of links between erosion and forcings.

2.2 Database design

To organise the disparate knowledge reported in the literature, a rigorous analytical framework is an absolute necessity upstream of any data capture. We opted for a relational data base framework whose architecture was designed according to the Merise method (Tardieu et al., 1985). Merise provides a formal methodology to describe entity-relationship data models. Each entity corresponds to a group of data framed into a table and containing different fields called attributes. The different entities are related to each other by well-defined relations. As an example the *cliff* entity contains information about cliff settings (Fig. 3). Each cliff description corresponds to a line in the *cliff* table and contains a unique primary key to identify this line/record. The *measure* entity contains information about cliff erosion. *Cliff* and *measure* are related through cliff erosion. The relation between an erosion record and its corresponding cliff is made by typing the cliff primary key. This conceptual exercise allows to optimize data capture and redundancy, to flag possible information duplicates and limits ill-conceived relationships. The database structure was implemented in OpenOffice Base that can be addressed by the statistical software R via SQL queries. Only the geographic fields (cliff location) were digitized in GoogleEarth and exported into shapefile with a key code or primary key linked to the relational database (in the sense of data science analysis).

Here, GlobR2C2 was structured with two objectives in mind: (i) compiling original information and faithfully tracing publication sources, and (ii) anticipating analytic queries of the database designed to answer geomorphological questions. The database is structured to keep track of information relative to publications, sites, measurements and contextual information of the cliffs, or their environment. Specific care was taken to separate original data from information derived by us, and distinguish between article information from auxiliary data sets (Fig. 3). The database contains entities coming from three type of sources: raw data from publications, raw data from gridded data (global reanalysis) and tidy covariates (derived from raw data).

The final conceptual data model contains 11 entities and 76 attributes. A conceptual model is given in figure 3. Entities refer to publications (*Publication and Author*), cliffs (*Cliff, Lithology, Geotechnical parameters, Cliff height*); erosion rate measurement (*Measure*) and forcing (*Climate, Swell, Tide*). Information contained in each entity come from publication except entities concerning forcings and *Geotechnical parameters* which come from external sources (Fig. 3). The relation between the different entities are explicitly described by the action verbs and the numbers represent the cardinality of the relation (eg. 1 cliff can corresponds to 1 or N erosion rate measurements, cardinality 1,N).

2.3 Database information fields

2.3.1 Raw data extraction: From publication and national databases

GlobR2C2 (Global Recession Rates of Coastal Cliffs) database v1.0 was populated with data coming from two main types of published sources: published peer-reviewed English journal articles, and official but non-peer-reviewed studies arising from official organizations (e.g. CEREMA French risk survey) in English, French or Spanish language. Journal articles were selected when they propose quantified values of cliff recession rate and describe the quantification method. The search was initiated with bibliographic web search engines (Web of Science, Google Scholar) and expanded using citations therein. We recognize that some references may have escaped our attention. We are keen to expand the database further with the contribution of the community. The version presented in this article is version 1.0. compiling references up to 2016.

2.3.2 Cliff and lithology description

The *cliff* and *lithology* entities contain information related to cliff morphology (i.e. height, length) and rock property (i.e. lithology, fracturing, weathering, folding, bedding).

Cliff geology may exhibit a very complex set of lithologic types, contact relationships, inherited tectonic structures and overprinted weathering. Authors often do not repport systematically on these characteristics. Confronted with of the heterogeneity of parameters presentation, we synthesized information in the following manner. A lithological name fills the *"lithology"* entity and a position field records rock position along the cliff (numbered from cliff toe to cliff top). Additional descriptions were copy/pasted in comment fields in order to preserve the original description. By comparison, rock state (weathering, folding, faulting, bedding etc.), is rarely mentioned. This could be because the cliffs do not present any such characteristics, or because authors did not think relevant to mention it. Moreover, parameters describing rock state are either complex or technically expensive to describe and quantify or outside the authors' scientific field of expertise. They were characterised with a Boolean value (True/False) to be integrated in the database. 'True' refers to the presence of fracturing/weathering mentioned in the paper. 'False' means either that authors describe fracturation/weathering as non existent/negligible or is not mentioned in the paper.

2.3.3 Cliff location

Cliff location is entered as a geographic coordinates. Studied cliff site extent was digitized from publication information and mapped using Google Earth. A primary key links this geographic file to the database.

2.3.4 Measurement description

The measure entity contains the erosion rate values and measurement methodology (how erosion was measured, for how long, with what detection threshold). Erosion is most of the time provided as an erosion rate in meters per year, occasionally as finite retreat (in meters), minimum and maximum erosion rates or eroded volume (in cubic meters).

Cliff retreat measurement errors and time spans were also recorded. Measuring sea cliff erosion presents a wide range of techniques. Those techniques vary significantly in terms of: (i) accuracy, from field observation and "expert" estimates May and Hansom (2003) of volume loss to precise measurement using for example lidar (e.g. Dewez et al., 2013) ; (ii) time period surveyed, from twenty minutes (e.g. Williams et al., 2018) to thousands of years (e.g. Choi et al., 2012; Hurst et al., 2017; Regard et al., 2012); and (iii) Spatial extent along the coast, from tens of meters (e.g. Letortu et al., 2015) to kilometres (e.g. Hapke et al., 2009). Moreover, these measurements can be divided into three classes of methods: 1D, 2D or 3D.

1D cliff retreat measurement techniques correspond to retreats calculated on single transects. Typically, they correspond to measurements done with peg transects recording the cliff toe retreat or transects on aerial photographs to quantify cliff-top retreat (Kostrzewski et al., 2015; Lee, 2008; Pye and Blott, 2015). 2D measurements are mostly based on aerial photograph comparison. They either quantify the area lost between two aerial photographs campaigns or average numerous transects (Costa et al., 2004; Letortu, 2013; Marques, 2006). 3D techniques record the evolution of the cliff face and quantify volumes (e.g. Letortu et al., 2015; Lim et al., 2005; Rosser et al., 2007). Initially, 3D assessment were performed based on observable, large, rockfall scars or debris apron, (e.g. May, 1971; Orviku et al., 2013; Teixeira, 2006) but now the two most used methods are lidar and SfM.

2.3.5 CEREMA French national dataset: a particular case

The French CEREMA institute published a systematic national coastal cliff recession inventory (Perherin et al., 2012) based on aerial photograph comparison every 200 meters stretch of cliff along the entire French metropolitan coastline (1800 km of coastal rocky cliff, it correspond to 465 (53%) values in the database). This rich systematic dataset was obviously included in GlobR2C2 but with two caveats. On the one hand, the CEREMA dataset introduces a strong spatial bias for French oceanographic and climatic conditions in the database observation records. This situation may risk to polarize analytical results but was recognized beforehand and specifically treated to prevent such bias (cf. part 4.2.3).On the other hand, being a systematic study for every stretch of coastal cliff around the country, it makes it more robust to scientific and funding biases. Research funds are often sought for areas combining coastal threats with societal interest. Coasts with higher recession rates are therefore more often sampled, while quiet stretches of coastlines remain in the shadows. Including this data therefore provides a more representative set of values existing along coastlines. Among little studied sectors this CEREMA study contains hard rock coastal stretches (e.g. hard proterozoic granites from French Brittany) and erosion rates lower than the study's detection threshold.

Based on historical aerial photograph archives, CEREMA acknowledges to that quality of photographs limits the detectable cliff recession to rates higher than 10 cm/yr. Below this value, they deem recession rates as undetermined. We chose to record those undetermined values in the database but not to use them in the statistical analysis. We discuss this choice in discussion section.

2.3.6 Tides

The tidal range describes the variation in height of the water surface. One consequence is that the cliff and platform undergo cyclic wetting and drying that weakens and erodes the constituting rocks (Kanyaya and Trenhaile, 2005). Rather than referring to difficult use tidal records from tide gages, tidal modelling was performed with FES 2012 software (Carrère et al., 2012). This model gives all the constituents of the harmonic tide analysis. For our analysis, 8 harmonics were considered: M2, N2, K2, S2, P1, K1, O1. Those harmonics represents diurnal and semi-diurnal main components of tide harmonic model. The model produces a time series between given start and stop dates of sea level within a regular grid of 0.25 degree. Tidal characteristics were retrieved for each study location for two entire years, from which the mean amplitude over two cycles was extracted (i.e. height difference between successive high and low tides).

2.3.7 Waves

Wave properties were extracted from ERA-interim reanalysis dataset (Dee et al., 2011). This gridded data has a pixel size of 0.75 degree. Temporally, data spacing is 6 hours during the 1979-2016 period. Wave assault was characterised both in terms of mean agitation and extreme events. Three mean parameters characterise wave assailing force: significant wave height of combined swell and wind, wave period and wave direction. For swell characteristics, mean significant wave height and wave period characterise the average sea agitation. The wave direction value records the most frequent wave direction for the duration of the reanalysis period (1979-2016).

Anticipating that mean sea state values may be deceptive metrics, a record of extreme events was also described. Those events were characterised by the 95 % percentile of wave significant height as suggested by Castelle et al. (2015). To complete this quantile value, the number of storms experienced at each cliff site was calculated between 1979 and 2016.

2.3.8 Climate

Climatic information was extracted from Climate Research Unit data between 1961 and 1990 (Mitchell and Jones, 2005). The grid size is 0.5 degree, at monthly time steps. Chosen parameters likely to influence erosion rate are mean annual rainfalls, mean monthly temperatures and number of freezing days (number of days per year below 0°C). We did not find a global climatic data set reporting time series of rainfall and temperatures spanning the durations covered by the articles contained in GlobR2C2.

2.3.9 Cliff height

Cliff height often appeared to be missing. Filling this value is not straightforward because cliff height can be strongly variable along the surveyed cliff. Nevertheless, in order to provide a robust estimate, a mean cliff height was extracted from the 8" global DEM (GMTED2010, Danielson and Gesch, 2011). Cliff height extraction consisted in computing a buffer around the cliff extension shapefile, in which the mean value of non-zero pixels (corresponding to the sea) is computed. To assess the accuracy of these cliff height estimates, they were compared against those rare values presented in publications. Computation is close to value given in publication with a root mean square error of 19 m at global scale. We deem it sufficient for a first attempt at the global scale, probably not greatly different from the cliff height accuracy in the publications.

2.4 Tidying the covariates: from database fields to predictors

The first purpose of the database is to collate raw data from original sources in the most traceable manner possible. This data does not necessarily report information in an easily accessible fashion. This may be because: (i) fields translate different realities (e.g. recession rates vs retreat values or recession rates relate to profile-specific recession rate or to kilometre long cliff sections), (ii) value instances of a field is too broad and needs summarizing in fewer categories (e.g. lithology). Thus, post processing was applied to the database in order to make it more homogeneous and more readily usable for statistical analysis.

2.4.1 Integration of punctual records

We mentioned earlier that measurement techniques were either 1D, 2D or 3D. These methods do not reflect exactly the same processes and a choice was made to force all measurements to homogeneously report 2D type measurements. The 3D measurements in $\mathrm{m}^3.\mathrm{yr}^{-1}$ were divided by cliff face surface in a cliff top equivalent retreat in $\mathrm{m}.\mathrm{yr}^{-1}$. 1D measurements do not average information laterally. Cliff retreat is stochastic in time and space and 1D measurements profiles may happen to quantify erosion on a particulary high or low erosion transect. Erosion rates of the transect measurements were therefore averaged for a unique study, cliff and period of time in order to limit the risk of over/under-representation.

2.4.2 Field unit conversion

Original data may be provided in different ways (for example the time span between two measurements may be given by a duration or start and end dates). As often as possible this information is summarized in a single duration field with homogeneous unit. This lists the operations performed:

- To obtain a duration in years, the fields measure duration [year], measure beginning and measure ending [date] were merged together.
- Retreat [m] and eroded volume [m^3] were converted to retreat rate [$\mathrm{m}.\mathrm{yr}^{-1}$].
- The mean cliff height is either obtained from a cliff height mean field or as the mean between height min, height max [m].
- The error [m/yr] is a compilation of error value and error type.

2.4.3 Average site climate

Some explanatory variables were strongly correlated with each other (e.g. wave period vs wave significant height). This redundant information may lead to spurious correlation. New synthetic variables combine existing variables.

- Monthly mean temperatures were converted into mean annual temperature and amplitude.
- Deep water swell energy flux was computed using swell period and significant height

  $$E_f = \frac{1}{8}\rho g H_s^2 C_g \qquad with \qquad C_g = \frac{1}{2} g \frac{T}{2\pi} \tag{1}$$

  Where ρ is water density; Hs [m] is significant wave height; Cg [$m.s^{-1}$] is wave group velocity; and T [s^{-1}] is wave period.
- Swell incidence with respect to the cliff.

2.4.4 Rock resistance inference

The database, filled with information from publications, results in more than 40 distinct lithological descriptions. We first grouped lithology into 9 groups with a similar classification to that of Woodroffe (2002) for historical comparison. But lithology alone does not govern rock mass mechanical properties. Tectonic inheritance, deformation, fracturing and weathering weaken the rock masses. Consequently, the rock constituting the cliffs are divided into rock mass strength criteria. Following the practical examples from Hoek and Brown (1997), we propose to further aggregate Hoek and Brown's macroscopic rock mass strength categories into three categories. Hoek and Brown (1997) describe field estimates of rock strength and experimental uniaxial compressive strength. They describe seven grades of rock resistance, from extremely weak to extremely strong. The table describing field estimates, resistance term, compressive strength and example is given in Table 1. This table is associated with our Hoek and Brown classification and associated lithologies found in the database.

Aggregation criteria are based on the fields lithology name, weathering, fracturing and comments, in which all published details on rock strength, structural geology, weathering were preserved. Rocks were classed into three resistance classes termed hard, medium and weak. One may note that a similar approach, but with only two classes, was adopted by the Eurosion project consortium (Doody and Office for Official Publications of the European Communities, 2004). Hard rock cluster together granite, gneiss and limestones. Weak rocks are mainly poorly consolidated rocks (weakly cemented sandstones, glacial tills and glacial sands) or strongly weathered rocks. Weak rocks noticeably include well studied chalk cliffs. Medium resistant rocks correspond to claystone shales and siltstones.

3 Analysis / Results

3.1 Database content, completeness

The database is filled with 58 studies, out of which 47 are peer reviewed articles and 11 are public national databases, documenting 1530 cliff sites and 1680 erosion rate records. Indeed, some cliff sites were repeatedly measured over different periods. With more than 90% of fields complete, the database is rather satisfactorily thorough. However, the constitution of the database highlights some characteristics that are often poorly reported. We mentioned previously the difficulty to find a description of cliff rock weathering and fracturing. Those fields are missing for 98.4% of records (corresponding to 53 publications).

3.2 Where was erosion measured?

Studies are mostly concentrated in Europe (42 studies, 1579 records), in Oceania, focused mainly on New Zealand (3 studies, 94 records) and Northern America (4 studies, 50 records). Asia (2 studies, 4 records) and South America (1 study, 1 record) are poorly represented. No literature was found for the entire African continent. This lack is confirmed by the absence of a chapter about Africa in Kennedy et al. (2014). Study locations are plotted in Fig. 4.

3.3 How was erosion measured?

The number of studies is steadily growing since the mid-1990s (Fig.5), for every method type. Older studies exist and are present in Sunamura's database, however those papers were not available and/or cliff and measure description were too poor to be encoded in our database. The most used method is the comparison of aerial photographs or historic maps, which correspond to a 2D method easy to apply and allowing erosion evaluation spanning several decades. Forty-three studies used this method representing 50% of published studies and 88% of the records. The second most used method is 3D type, which has become common from mid-2000. It represents 19 studies (22%) and 5% of records. Finally, some other methods are occasionally used. The 1D methods represent 8 studies (9%), 3.5% of the records.

Reported studies describe coastal processes along 20 m to 6.4 km stretches of coastline. The median length is 600 m. Total survey duration vary from just 1 month to 7'100 years, but half the data lie between 56 and 63 years given the bulk of aerial photograph comparison studies.

3.4 Examining relations between erosion rate and forcings

The purpose of the database is to examine the relationships between erosion rates, site conditions and external forcing. Those links were sought by means of statistical exploration data analysis (known as EDA).

3.4.1 Erosion vs rock mass properties

One of the first influencial factor often pointed to in literature is rock resistance (e.g. Benumof et al., 2000; Bezerra et al., 2011; May and Heeps, 1985; Costa et al., 2004). Figure 6 shows erosion rate distributions for the three rock resistance classes based on Hoek and Brown criterion. Three distinct behaviours can be seen. Hard rock (341 observations) erodes at a median rate of 2.9 $\mathrm{cm.yr^{-1}}$ with a Median Absolute Deviation (MAD) of 3.4 $\mathrm{cm.yr^{-1}}$. Medium resistance rock coasts (63 observations) erode at around a median value of 10 $\mathrm{cm.yr^{-1}}$, with a MAD of 7.8 $\mathrm{cm.yr^{-1}}$. Due to the small number of observation of medium resistance rocks, this resistance class should be considered carefully. Finally, weak rocks (403 observations) erode at a median value of 23 $\mathrm{cm.yr^{-1}}$ and reach rates higher than 10 $\mathrm{m.yr^{-1}}$ with a MAD of 25 $\mathrm{cm.yr^{-1}}$.

Macroscopic rock mass strength classes, though possibly crude, exhibits the ordered behaviour expected by literature: weak rock erodes faster than medium strength rock, and medium strength rocks erode faster than hard rocks. Central erosion rate values increase by a factor 2 to 3 from one class to the next.

These values are in agreement with Woodroffe's work (2002), but, even if those distributions are distinct, they are broadly spread and multimodal.

3.5 Erosion vs marine forcings

In order to explore the influence of sea aggression, several variables were implemented in the database describing mean sea agitation and tidal range, and sea agitation during extreme events. All the variables concerning swell are strongly correlated.

Hence, only three independent marine parameters are analysed in the following scatterplots (Fig.7): tidal range, wave energy flux and number of storms.

All scatterplots appear to be widely spread and do not show simple linear relations. Indeed, Spearman's rank correlation coefficients, which evaluates monotonic relations between two variables, are low (Fig. 8). Furthermore, many tentative correlations cannot be trusted (p-value > 0.05). Those correlations and associated p-values are given in Figure 8. Exploration of marine forcings indicates that none have an apparent effect on erosion rates, other than a weak relation between tidal range and erosion rates suggesting higher erosion for tidal ranges between 1 and 3 meters (yet not visible for medium resistant rocks).

3.6 Erosion vs climatic forcings

Concerning climatic forcings, recession rates are compared to temperature variation, frost frequency and amount of rainfall. As for marine forcings, data is very scattered (Fig.9). Frost day frequency and rainfall show a positive trend with erosion rate for weak resistance rocks. Poorly consolidated rocks represents the large majority of rock type present in cold (>50 frost day per year) and rainy climates (> 1000 $\mathrm{mm.yr}^{-1}$) in the database. Only a few studies concern harder rocks under cold climate. However, even if a trend exists, data are widely distributed and Spearman's rank correlation coefficient is low (0.25 for frost, 0.07 for rainfall). Mean annual temperature does not show any clear correlation with erosion rate.

4 Discussion

4.1 Comparison to previous studies

The GlobR2C2 database provides a quantitative overview of current coastal rocky cliff erosion knowledge. This database is the first update since Sunamura's 1992 seminal publication and adds 54 additional quantitative studies to the scientific debate. Its design allows for an assesment of the drivers of erosion. Historically, Woodroffe (2002) already tried to link erosion with lithology in a broadly reproduced graphic. This graph shows a clear pattern of increasing erosion rates with decreasing rock resistance. GlobR2C2 updates this classic graph using the same lithological classification (Fig.10). New knowledge does not change historical views, but narrows down assumed erosion rate ranges both towards lower and higher rates. We also observe that supposed hard rocks such as granites or basalts can erode as quickly as 1 $\mathrm{m.yr}^{-1}$. This is because resistance to erosion does not depend on lithological category alone, but also on the degree of weathering, jointing, folding, etc (Cruslock et al., 2010; Stephenson and Naylor, 2011; Sunamura, 1992). Figure 10, presented at a conference with sedimentologists triggered strong reactions due to the lack of rock robust classification in their community. This result confirms the choice for a less debatable rock resistance criterion instead of lithology. This geotechnical criterion is not perfect either. It was inferred based upon authors' description of the cliff, thus it can include a part of interpretation and some degree of uncertainty.

4.2 What knowledge does GlobR2C2 compile?

The GlobR2C2 database is based on bibliographic references as well as models and reanalysis used as proxies for forcings. Some biases are inherent to this kind of approach. The next paragraphs focus on different aspects of these limitations due to the use of: (i) cliff retreat rate as a proxy of erosion, (ii) the use of model and reanalysis as proxy of forcing, (iii) the use of peer-reviewed journals.

4.2.1 Erosion rates, study duration and stochastic behaviour

Statistical exploratory data analysis is a way to dissolve local particularity into a global analysis. Nonetheless, including every quantitative study implies mixing rates measured by different methods, accuracy, spatial and temporal extents, which could be a source of bias. Erosion is stochastic: the occurrence of a big rare event would influence the actual figure of the observed retreat rate. Rohmer and Dewez (2013) for instance, describe statistical indicators for testing the outlier nature of very large rock falls, with methods borrowed to hydrology, seismology and financial statistics. These indicators were applied to a chalk cliff site in Normandy (northern France) in Dewez et al. (2013). During the 2.5 years terrestrial lidar monitoring period, a massive 70'000 m^3 rock fall caused a local cliff top retreat of more than 19 m (Dewez et al., 2013). That is more than one hundred years' worth of average retreat in one event. Estimated annual cliff recession rate rose from 13 $\mathrm{cm.yr}^{-1}$ to 0.94 $\mathrm{m.yr}^{-1}$, a seven-fold increase, just by including this random, and definitely unrepresentative event (Dewez et al., 2013). Further demonstration is brought by other studies covering the same site. Costa et al. (2004) had estimated the recession rate to be ca. 15 $\mathrm{cm.yr}^{-1}$ in 29 years from aerial photos. And Regard et al. (2012), using millennial recession rates from ^{10}Be accumulated in flint stones exposed in the chalk coastal platform, obtained 11 to 13 $\mathrm{cm.yr}^{-1}$ over 3'000 years.

GlobR2C2 therefore addresses the concern of non-representative erosion values by compiling all studies available online, and retaining information from all sites and survey periods. In doing so, the actual dispersion of recession rate values is preserved and allows for recognizing outlying values (Fig.11).

4.2.2 Forcing proxies

While publication-derived cliff recession rates and cliff conditions could be forced into a coherent database framework, environmental forcings were so scarcely and heterogeneously documented that the same rationalization process was not possible on the publication basis alone. Instead, publicly available global climatic and sea condition databases were used. These databases present the advantage of being spatially and temporally continuous thanks to reanalysed climate and sea state models. Their principal limitation is their coarse-grained definition compared to site specificities. Nevertheless, they document external forcings (i) in a uniform fashion (regular spatial and temporal sampling steps), (ii) for the entire globe, and (iii) reflect forcing condition for durations spanning several decades. So, even if regional or continental data sets offer more high-resolution information in space or time, the global extent ensures that all cliff sites worldwide are documented uniformly.

4.2.3 Literature biases as future tracks to improve cliff evolution understanding

GlobR2C2's worldwide compilation shows that research in this domain is very active. A large body of quantitative data already exist. However, even if data coverage is somewhat global, publications turned out to focus mostly on a few western countries. This finding reflects the strategy of literature search adopted: only international and national literature published in English, French or Spanish were compiled. Due to the language barrier, we are aware that studies in Russian, German or Japanese languages, among others, were unwillingly omitted.

Spatially, our search strategy did not flag scientific literature on the evolution of African and South American cliffs. Cliff recession studies appears to be focused on the richest areas where economically valuable coastal assets are exposed to losses. This geographic distribution induces an over-representation of temperate climates and a limited presence of some extreme climates or wave conditions like equatorial or polar regions. Those extrema could nevertheless be a key for understanding effects of climate and wave conditions on cliff erosion.

Studies also focus on fast eroding coasts because they represent bigger risks and also because of methodological limitation. Indeed, the French CEREMA study brings the majority of erosion values for hard rocks (265 values over 343, 77%) and medium rocks (47 values over 66, 71%). Without this systematic study soft rock represents 75% of measured cliff retreat. This fact biased the analysis by mostly documenting erosion distribution in higher values. The weight of this bias can be appreciated thanks to the French CEREMA study. This study contains null erosion values for coastal sectors where the cliff was not seen to recess in a detectable manner on historical photographs. Yet this detection threshold is deemed to be of the order of 10 $\mathrm{cm.yr}^{-1}$ (Perherin et al., 2012), which is rather high, and null recession could reflect erosion situations anywhere in the spectrum between 0 and 10 $\mathrm{cm.yr}^{-1}$. These null values represent 67% of the studies of rocky coasts, which means that slowly eroding rocky coasts are common and ignoring this information can affect conclusions. In order to check the importance of the bias induced by those values, we explored two extreme cases. The erosion value was set to either a small value of 1 $\mathrm{mm.yr}^{-1}$ or to the detection threshold of 10 $\mathrm{cm.yr}^{-1}$. Table 2 shows the influence of the null value in the distribution of erosion rate for the three Hoek and Brown rock strength classes. While the median and quantile absolute values are affected by the value attributed to null observations, the expected order of rock sensitivity to erosion is maintained. Weak rocks erode at higher rates than medium and hard rock. Therefore, we trust this result. Further, the dependency relationships flagged earlier remain. A weak positive correlation still exists between frost day frequency and a maximum tidal efficiency for tidal range between 1 and 3 m still is observed.

4.2.4 Cliff retreat vs platform evolution and rock coast erosion

The cliff retreat rates discussed here cannot capture the overall rock coast erosion complexity. In particular, it is obvious that the rock shore platform coevolves with the cliff (e.g. Sunamura, 1992; Moses and Robinson, 2011; de Lange and Moon, 2005). Sunamura (1992) proposes that the shore platform erodes vertically at a rate proportional to its dip and cliff retreat. The processes driving this vertical erosion are numerous (cf. introduction). It has also been proposed that the shore platform width reflects the total cliff retreat since the Holocene transgression and thus the average rock coast erosion since then (cf. Regard et al., 2012). Applied to our findings, these ideas imply that harder rocks leading to slower cliff retreat come with steeper platform slopes.

On the one hand, platform width may be a powerful proxy to long-term cliff retreat. This analysis is not currently possible due to the fact the seaward platform boundary is not obvious (Kennedy, 2015). As well as a lack of worldwide information on rock shore platform widths. On the other hand, this idea is debated, because it implicitly favors the static model for the evolution of shore platform instead of the equilibrium model (see de Lange and Moon, 2005; Stephenson, 2008; Moon and de Lange, 2008; Dickson et al., 2013).

Beyond its width, the rock platform behaviour encompasses the dynamics of scree apron lying on it and possibly shielding it from sea action (cf. Regard et al., 2013). Indeed, cliff collapse is the only stage within platform/cliff erosion cycle leading to apparent retreat. This transitory character could lead to long-term cliff retreat rate under- or overestimation. Working with an important dataset like the one presented here averages data variability, ensuring the extrema are not over-represented (cf. section 4.2.1).

4.2.5 Toward a new rocky coast cliff research agenda

This bibliographic synthesis has highlighted the strengths and weaknesses of the current rocky coast research efforts. The last three decades's trend has gone towards increasing the quality and the resolution of cliff recession data and documenting a growing number of sites; which is good. What this study highlights however is a lack of description of critically useful parameters to understand cliff evolution dynamics: (i) cliff height; (ii) finer rock mass characteristics description, in particular weakening phenomena such as weathering and fracturing; and (iii) foreshore description, in particular its type (sand beach/pebble beach/rock platform) and geometry (elevation, slope, width). Moreover, the geographical distribution of studied sites highlights a major gap of knowledge under extreme climates (tropical, equatorial and glacial) or for slowly retreating cliffs and for medium resistance rock types. We also found that literature concerned with cliff retreat was not simultaneously trying to link shore platform processes to cliff retreat or how local variations affected cliff retreat specifically.

5 Conclusions

Compared to continental cliffs, coastal cliffs obviously erode quicker because of the sea presence. The GlobR2C2 v1.0 database compiles ca. 2000 coastal rocky cliff retreat data from an online global literature search published before 2016. It is the first attempt of this kind since Sunamura's seminal publication in 1992. The investigated period adds information arising from the quantitative revolution of lidar technology, structure-from-motion (SfM) technique, accessible to scientists with little background in photogrammetry and massive release of aerial photographic archives of mapping agencies from western countries. The data compiled in GlobR2C2 is heterogeneously distributed in terms of retreat rates, geographical location, cliff nature and climate settings. Even if further research should aim at completing little studied geomorphic contexts of the globe, existing information clearly shows that cliff retreat is most clearly governed by the lithological nature of the cliffs. The dependence of cliff recession rates on rock types is best expressed using a geotechnical parameter, the Hoek and Brown (1997) macroscopic rock mass strength parameter. Rocks classified as weak (recession rate median: 23 $\mathrm{cm.yr^{-1}}$) erodes 2-3 times faster than medium strength rocks (median rate: 10 $\mathrm{cm.yr^{-1}}$), themselves erode 2-3 times faster than hard rocks (median rate: 2.9 $\mathrm{cm.yr^{-1}}$). Using solely a lithology denomination in the way of Woodroffe (2002) historical graph (Fig.10), lithologic types exhibit a similarly ordered behaviour (Fig.6), even if geologists contest the robustness of these denominations as proxies for rock strength.

Together with cliff settings compiled from publications, GlobR2C2 also records continental climate and marine conditions at study sites from reanalysed models for their global, spatial and temporal sampling regularity. Both forcings exhibit weak relations with cliff recession rates. In relative terms, however, climate (i.e. frost days frequency) exhibits a stronger influence than marine forcing. Influence of the sea is only slightly visible in this dataset through a maximum efficiency of erosion for tidal ranges between 1 and 3 meters.

Our data divides into three classes of resistance, following the Hoek and Brown parameter. The most resisting (respectively least resisting) rocks are found to lead to retreat rates less than 10 $\mathrm{cm.yr^{-1}}$ (83% quantile) (respectively up to 85 $\mathrm{cm.yr^{-1}}$). Medium-resistance rocks are not studied enough to give a precise range of retreat rates. Climate seems to be more efficient and frost seems to have the strongest influence.

We conclude at this stage that coastal rocky cliff erosion is primarily driven by cliff settings with second-order but non-negligible modulations by marine and continental forcings (Fig.2). These findings are of primary interest for coastal erosion models which, up to now, focus mostly on marine forcing (e.g. Anderson et al., 1999; Trenhaile, 2000; Limber et al., 2014).

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Figure 1. Evidence of sea driving coastal cliff erosion. The vertical shaped cliff in the foreground is similar to that in the background ()with smoothed shape) except that the one in the background has been protected from the sea by a sand spit. Obviously, the cliff with sea at its base retreats faster (the cliff face is more or less vertical). Photo from Punta Quilla, Patagonia, Argentina.

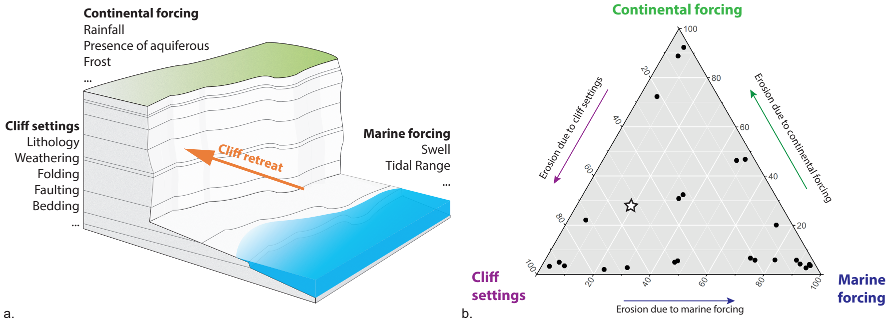

Figure 2. a. Sketch diagram of rocky cliff erosion drivers. b. Relative cliff retreat drivers reported from published literature in GlobR2C2. Factors of influence are grouped within three main classes: (i) “marine forcing”, (ii) “continental forcing” encompassing weather conditions and continental groundwater, and (iii) “cliff settings”. Responsible forcings cited by authors in publication’s abstract is summarised as a percentage of those three forcing based on abstract content. The star anticipates our position given the results emerging from the GlobR2C2 data base.

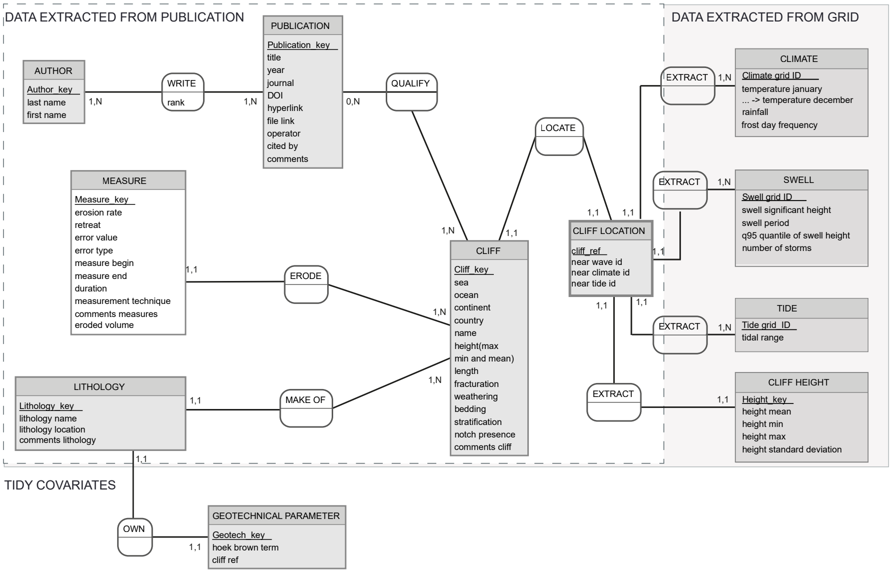

Figure 3. Conceptual data model of cliff erosion database GlobR2C2. Primary keys are underlined and numbers are cardinalities.

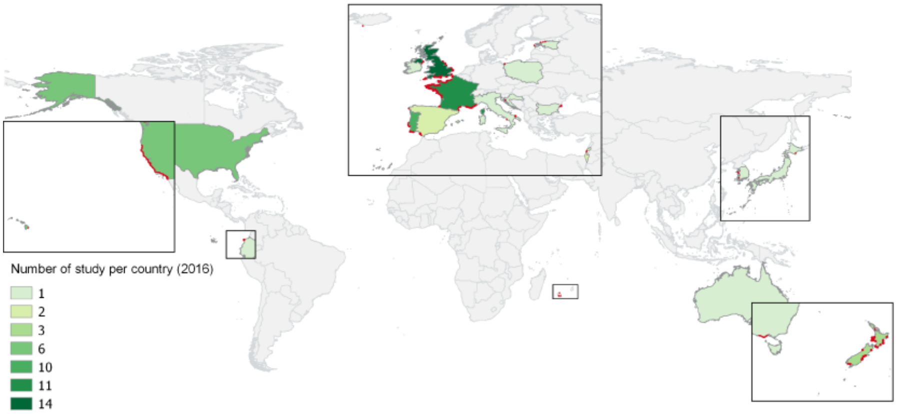

Figure 4. Cliff site locations (red dots) and number of studies by country contained in the database GlobR2C2 (published before 2016)

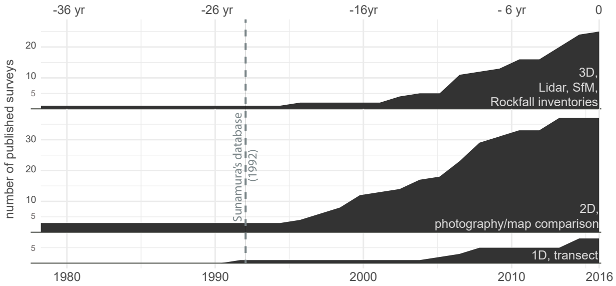

Figure 5. Time line of cliff erosion publications recorded in GlobR2C2 differenciated by measurement method.

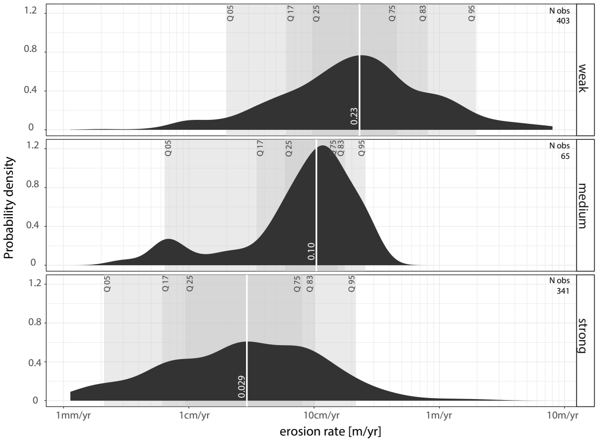

Figure 6. Cliff recession rates differenciated using Hoek and Bown rock mass strength criterion, which merges lithological descriptions and fracturing/weathering state of the cliff rock.

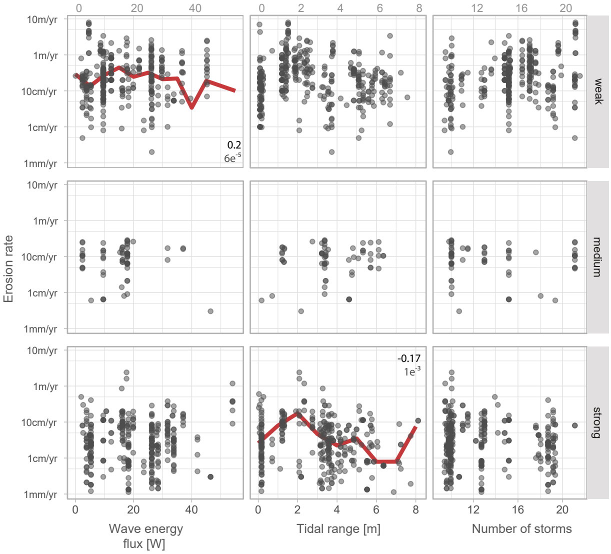

Figure 7. Erosion rate versus marine forcings (wave energy flux [W], tidal range [m] and number of storms) for each one of the Hoek-Brown rock resistance class. Lines beneath scatterplots represents moving median per bin and numbers are Spearman's correlation coefficient. They were only repesented when p-value was significant.

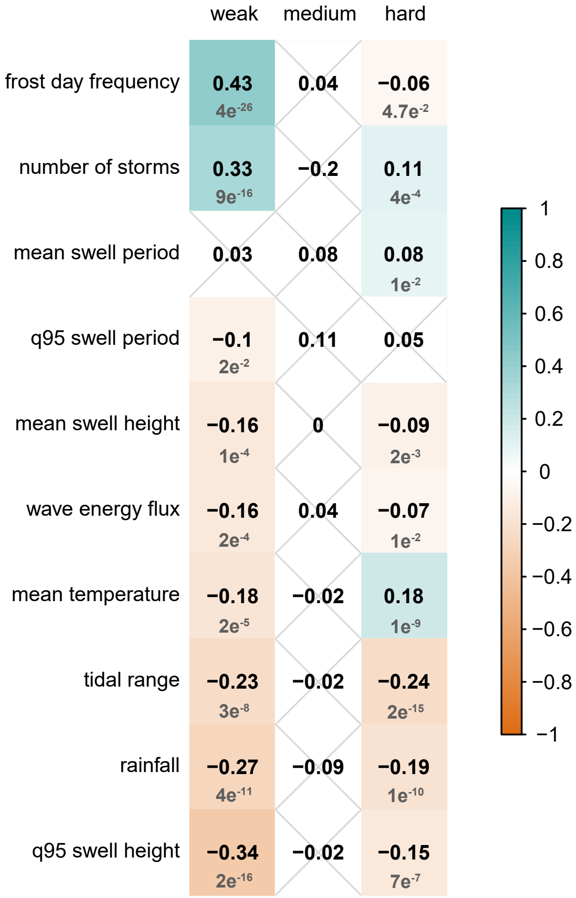

Figure 8. Spearman's rank correlation matrix between forcing and erosion rate for the three types of rock resistance. Values in black are Spearman's correlation coefficients. Grey values are associated p-values when significant (< 0.05).

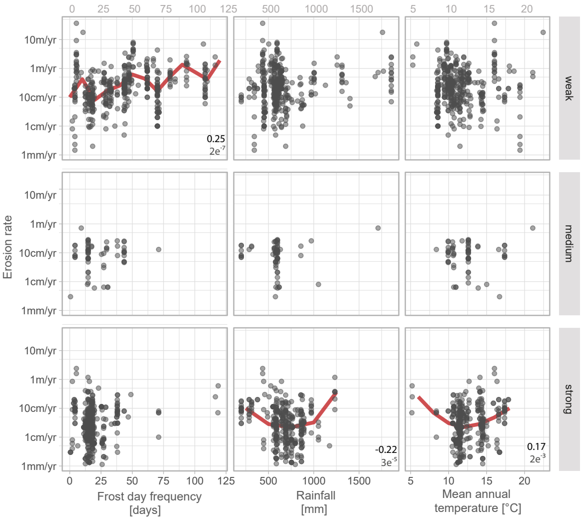

Figure 9. Erosion rate versus climate forcings (frost day frequency [days], annual cumulated rainfall [mm] mean annual temperature [°C] for each one of the Hoek-Brown rock resistance class. Overprinted lines on scatterplots represent moving median and numbers are Spearman's rank correlation coefficient. They were only represented when p-value was significant (>$2e^{-2}$).

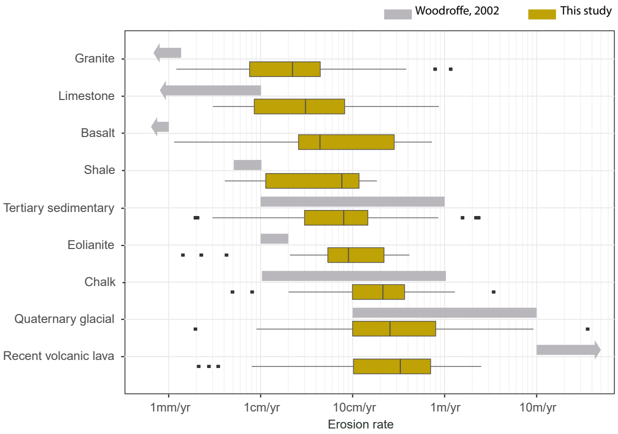

Figure 10. Ranges of erosion rate within different lithology. Comparison between Woodroffe's 2002 study and this one.

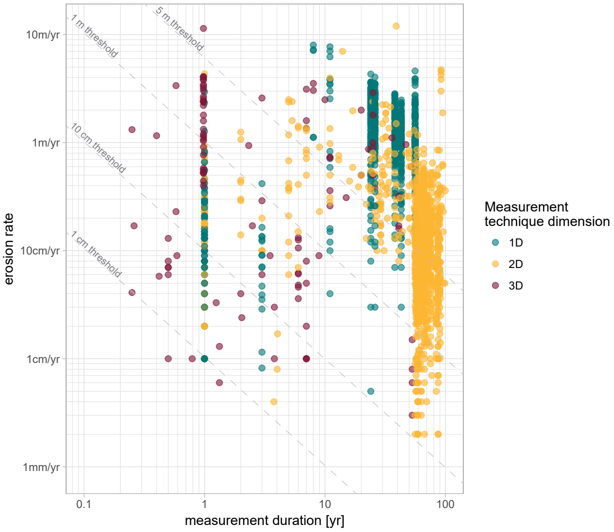

Figure 11. Survey time versus erosion rate by groups of measurement techniques.

Table 1. Field estimates of uniaxial compressive strength (Hoek and Brown, 1997) associated with Hoek and Brown term in the database and corresponding lithologies in the database.

Hoek and Brown table						Recorded in GlobR2C2 as	
Grade	Term	Uniaxial Comp. Strength (Mpa)	Point Load Index (Mpa)	Field estimate of strength	Examples	Hoek and Brown term	Unique lithologic name instances
R6	Extremely strong	> 250	> 10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite	hard	basalt, conglomerate, flysh, gneiss, granite, greywacke, intermediate rocks, lavas (basalts, etc), limestone, marly limestone, metamorphic, mudstone, plutonic, sandstone, schist, shale, siltstone, volcanic rock, volcano-sedimentary
R5	Very strong	100 -250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone,marble, rhyolite, tuff		
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale		
R3	Medium strong	25 - 50	1 - 2	Cannot be scrapped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone	medium	claystone, shale, slate, volcanic tuff, sandstone, shale, limestone, marl, siltstone, basalt, marl and consolidated clay
R2	Weak	5 - 25	†	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow whith point of a geological hammer	Chalk, rocksalt, potash	weak	aeolianite, argilites, basalt, chalk, clay, conglomerate, dune deposits, fluvial deposits, glacial deposits, glaciofluvial, gravels, head, lahar deposits, loess and silts, marl, sand, sand , sandstone, scories, silt, till, tuff, undifferentiated recent marine deposits
R1	Very weak	1 - 5	†	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock		
R0	Extremely weak	0.25 - 1	†	Indented by thumbnail	Stiff fault gouge		

† Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield highly ambiguous results.

Table 2. Distribution characteristics of cliff erosion rates (in m.yr-1) compiled from publications in GlobR2C2 differenciated by Hoek and Brown rock resistance types. The table's different lines reflect how characteristic distribution values change by changing the erosion rate value affected to cliffs instances where erosion rates were smaller than the detection threshold in the CEREMA study (n instances for N total observations). Null values were handled in three different ways: (i) insignificant rates removed from distribution computation; (ii) Null values are used and assigned an arbitrary low erosion rate of 0.001 m.yr-1; (iii) Null values are used and assigned an arbitrary rate of 0.1 m.yr-1.

	weak rock cliffs					medium rock cliffs					hard rock cliffs				
	Q5	Q17	Q50	Q83	Q95	Q5	Q17	Q50	Q83	Q95	Q5	Q17	Q50	Q83	Q95
null removed	0.018	0.1	0.23	0.85	2.499	0.006	0.063	0.104	0.18	0.269	0.002	0.01	0.029	0.106	0.286
null = 0.001	0.001	0.006	0.129	0.683	1.806	0.002	0.049	0.102	0.18	0.269	0.001	0.001	0.001	0.024	0.112
null = 0.1	0.01	0.1	0.129	0.683	1.806	0.006	0.063	0.102	0.18	0.269	0.006	0.1	0.1	0.1	0.112