

# **New coasts emerging from the retreat of Northern Hemisphere marine-terminating glaciers in the twenty-first century**

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### Supplementary Information:

- Supplementary Tables S1-S3 and Figures S1-S4
- Supplementary Analysis 1

### Supplementary Tables and Figures

| Region         | Gained coastline    |            | Lost coastline     |            | Glaciers with new coastline (%) | Glacier retreat area (km <sup>2</sup> /glacier) | New coastline (km/glacier) | New coastline-retreat area ratio (km/km <sup>2</sup> ) |
|----------------|---------------------|------------|--------------------|------------|---------------------------------|-------------------------------------------------|----------------------------|--------------------------------------------------------|
|                | (km)                | (%)        | (km)               | (%)        |                                 |                                                 |                            |                                                        |
| Arctic Canada  | 49.8 ± 0.2          | 2.0        | 0                  | 0          | 88.4                            | 0.2 ± 0.1                                       | 0.6 ± 0.02                 | 2.95                                                   |
| Arctic Canada  | 238.8 ± 0.3         | 9.7        | 8.8 ± 0.04         | 16.6       | 79.0                            | 2.2 ± 0.5                                       | 0.9 ± 0.02                 | 0.42                                                   |
| Alaska         | 90.3 ± 0.1          | 3.7        | 5.0 ± 0.05         | 9.3        | 71.4                            | 1.4 ± 0.3                                       | 2.0 ± 0.02                 | 1.41                                                   |
| Russian Arctic | 235.5 ± 0.3         | 9.6        | 2.8 ± 0.01         | 5.2        | 47.7                            | 2.7 ± 0.7                                       | 0.6 ± 0.01                 | 0.21                                                   |
| Svalbard       | 218.1 ± 0.2         | 8.9        | 33.3 ± 0.05        | 62.6       | 72.9                            | 2.9 ± 0.8                                       | 1.1 ± 0.02                 | 0.39                                                   |
| Iceland        | 3.7 ± 0.02          | 0.1        | 0                  | 0          | 100.0                           | 5.7 ± 0.3                                       | 3.7 ± 0.02                 | 0.64                                                   |
| Greenland      | 1629.3 ± 0.6        | 66.1       | 3.4 ± 0.04         | 6.3        | 78.7                            | 7.2 ± 0.9                                       | 2.2 ± 0.02                 | 0.30                                                   |
| <b>Total</b>   | <b>2465.5 ± 0.8</b> | <b>100</b> | <b>53.1 ± 0.10</b> | <b>100</b> | <b>71.0</b>                     | <b>4.4 ± 0.7</b>                                | <b>1.4 ± 0.02</b>          | <b>0.32</b>                                            |

Table S1. Regional characteristics of coastline changes. For gained and lost coastline an absolute value is given for every region, as well as a percentage of the summed length for the hemisphere. The percentage of glaciers with new coastline is calculated only for marine-terminating glaciers.

| No. | Location             | Name        | Area (km <sup>2</sup> ) | Year of appearance | Centroid                  |
|-----|----------------------|-------------|-------------------------|--------------------|---------------------------|
| 1   | West Greenland       | -           | 0,5                     | 2006               | 72°47'07"N,<br>54°21'43"W |
| 11  | North-East Greenland | -           | 1,4                     | 2008               | 81°28'02"N,<br>26°39'32"W |
| 12  | North-East Greenland | -           | 2,8                     | 2007               | 81°27'51"N,<br>26°29'48"W |
| 13  | North-East Greenland | -           | 2,8                     | ~ 2016             | 81°45'44"N,<br>14°37'57"W |
| 14  | North-East Greenland | -           | 34,0                    | 2012               | 79°08'38"N,<br>19°23'14"W |
| 15  | North-East Greenland | -           | 0,7                     | 2012               | 78°59'54"N,<br>19°10'08"W |
| 16  | North-East Greenland | Achtonfriis | 8,2                     | 2012               | 78°57'37"N,<br>19°13'30"W |
| 17  | North-East Greenland | Schnauders  | 182,2                   | 2012               | 78°46'45"N,<br>19°26'17"W |
| 26  | South-East Greenland | -           | 23,7                    | 2014-2015          | 67°23'00"N,<br>33°23'58"W |
| 27  | South-East Greenland | -           | 0,7                     | 2017               | 64°31'12"N,<br>40°15'17"W |
| 28  | South-East Greenland | -           | 1,7                     | 2003-2004          | 63°45'33"N,<br>40°34'03"W |
| 29  | South-East Greenland | -           | 0,7                     | 2004               | 61°26'52"N,<br>42°33'20"W |
| 35  | Severnaya Zemlya     | -           | 0,9                     | 2012-2013          | 79°51'28"N,<br>97°49'14"E |

Table S2. Newly identified Islands; 12 and 14-17 are presented as isolated on maps from the 1960s, then were connected to the glacier in 2000 and lost this connection before 2020.

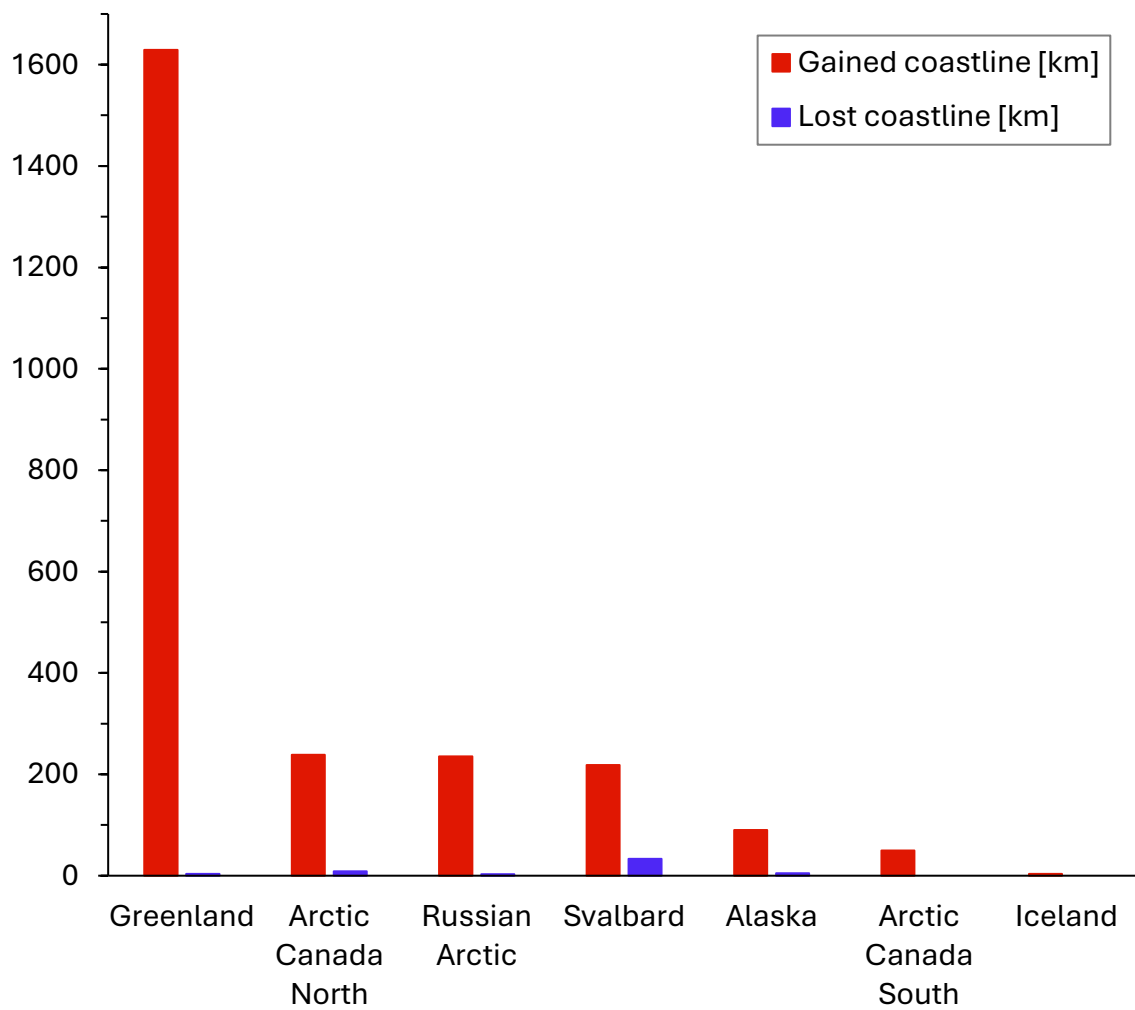
1

|                              |          | Annual precipitation [mm] |         |          |        |       |
|------------------------------|----------|---------------------------|---------|----------|--------|-------|
|                              |          | 0–200                     | 200–500 | 500–1500 | > 1500 | sum   |
| Mean annual temperature [°C] | < -10    | 6.5%                      | 21.5%   | 2.7%     | -      | 30.6% |
|                              | -10 – -5 | -                         | 10.1%   | 18.8%    | 1.2%   | 30.1% |
|                              | -5 – 0   | -                         | 2.1%    | 16.0%    | 16.8%  | 34.9% |
|                              | > 0      | -                         | -       | -        | 4.4%   | 4.4%  |
|                              | sum      | 6.5%                      | 33.7%   | 37.5%    | 22.4%  | 100%  |

Table S3. Mean annual temperature and annual precipitation in the areas of the new coasts. Percentage given for the length of new coastline in each climatic zone.

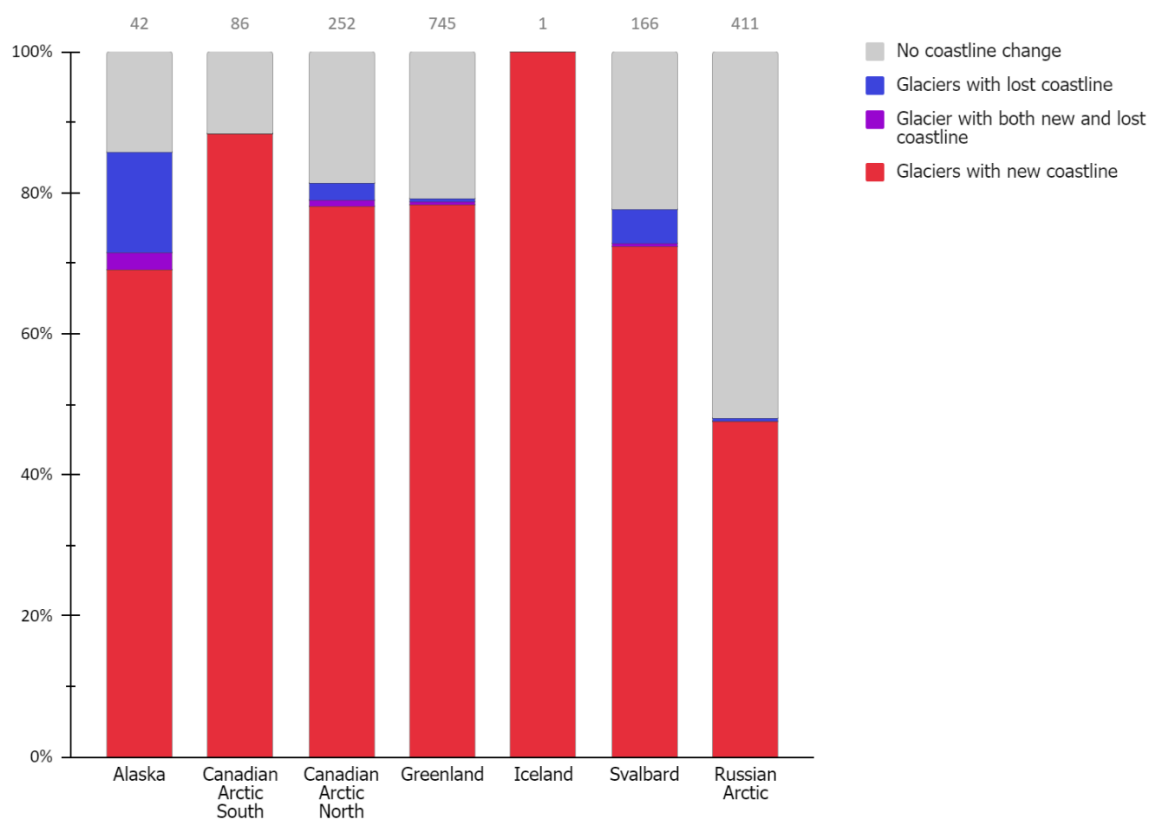
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6 Figure S1. Gained and lost coastline length presented by regions.



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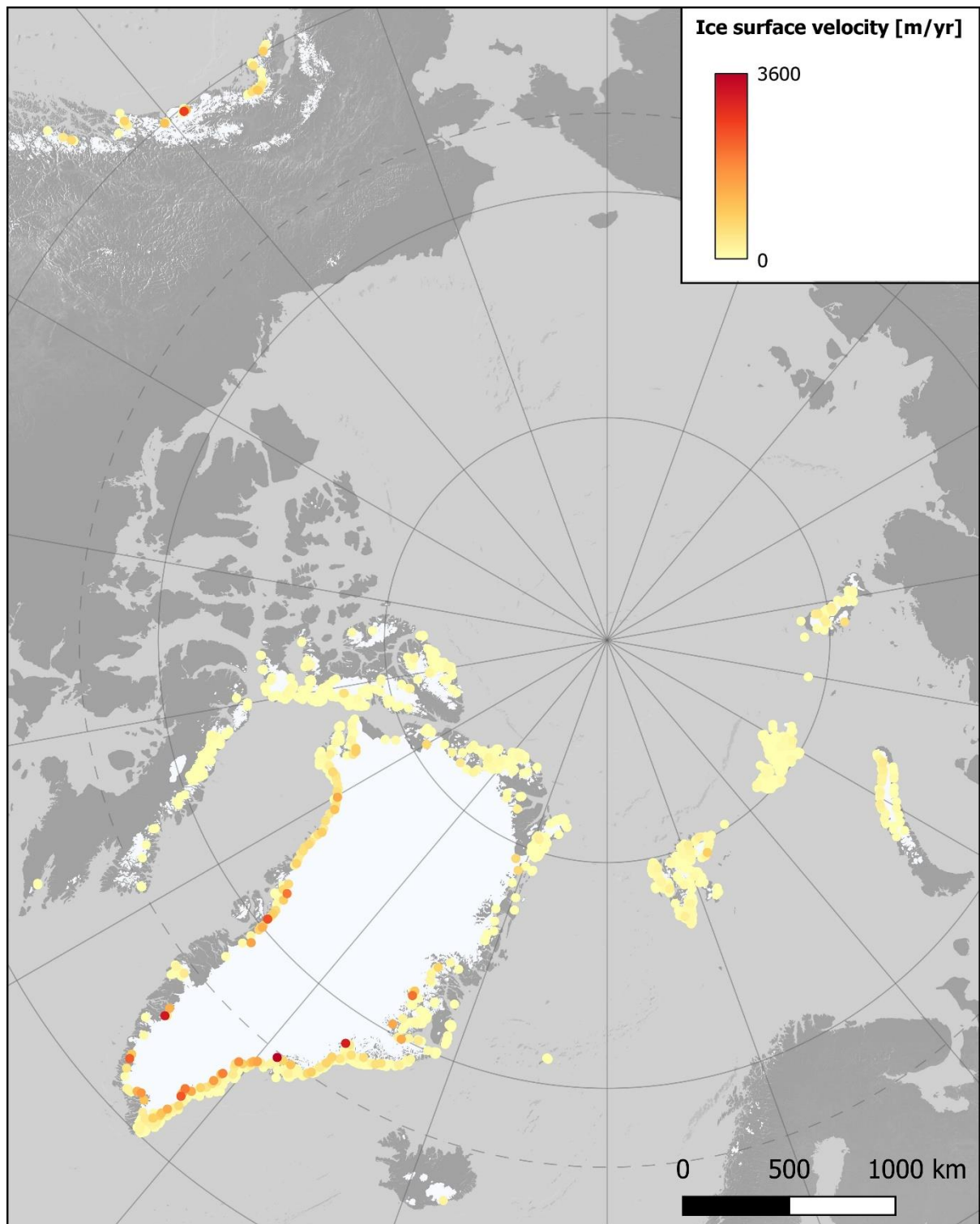
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Figure S2. Marine-terminating glaciers in the study regions divided into the ones which in the period 2000-2020: retreated leading to new coastline emergence, advanced leading to coastline loss, caused both emergence and loss of coastline, caused no coastline change. The total number of marine terminating glaciers in the region is given in grey on the top of each bar.



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Figure S3. Glacier surface flow velocity of north hemisphere marine-terminating glaciers (ITS\_LIVE dataset) extracted near the termini of each glacier (Kochtitzky et al., 2022). The highest values are displayed in the front.

## **Supplementary Analysis 1 – rock type as a factor affecting coastline gain effectiveness**

### **Introduction**

In the main text we state that the retreat of marine-terminating glaciers is the first-order control on the amount of new coastline emerged. However, by calculating the new coastline-retreat area (NC-RA) ratio we show also that there must be other essential controls as the ratio varies greatly between regions (Figure 3). A relatively short period of time from coastline emergence (1-20 years) did not allow us to find wide-spread large geomorphological coastal changes. As a result, the topography of glacier valleys seems to determine the new coastline detected. Valley topography in turn is to a large degree an effect of rate and spatial characteristics of glacial erosion (e.g. [Prasicek et al., 2015](#); [Louis 2021](#)), which is regulated by numerous processes, one of which is geological conditions (e.g. [Bernard et al., 2021](#)). Softer lithologies, such as sedimentary rocks, are generally more susceptible to glacial erosion due to their lower resistance compared to harder igneous or metamorphic rocks. For example, [Lane et al. \(2015\)](#) highlighted that softer rocks in the Uummannaq region of West Greenland are more prone to both basal and lateral erosion, which facilitates the development of efficient glacial systems. Glacial erosion in regions with soft Mesozoic and Cenozoic sedimentary rocks has been considerably deeper compared to harder rock formations, suggesting that the lithological composition plays a crucial role in determining erosion rates ([Hall et al., 2013](#)). This efficiency can be attributed to several mechanisms, including the susceptibility of softer rocks to both basal and lateral erosion, as well as the dynamics of glacial flow and the presence of pre-existing fractures. In general, glaciers exert greater erosive power in areas where the bedrock is less resistant, leading to more pronounced glacial features ([Tomkin, 2007](#); [Evans, 2020](#)). In contrast, harder rocks often require higher pressures and more complex processes, such as hydraulic jacking, to be effectively eroded ([Krabbendam et al., 2022](#)).

We decided to examine the relationship between NC-RA ratio and geology represented by two general classes of sedimentary strata and other rocks. The rationale behind such divide is that sedimentary rocks are in general less resistant to erosion than igneous and metamorphic rocks (e.g. [Montgomery 2004](#); [Buertey et al. 2016](#); [Hu et al. 2023](#)). NC-RA ratio (km/km<sup>2</sup>) is used instead of unnormalized length (km) with the intention of excluding the impact of glacier retreat.

### **Methods**

As explained in the main Methods, short new coastline segments (about 500 meters or less) were created and rock type was attributed to each based on the geological map of the Arctic ([Harrison et al. 2011](#)) in QGIS. Rock type classes included only: 1) sedimentary rocks, 2) not sedimentary rocks, 3) undivided. Class 2 included all categories of a) igneous and b) metamorphic rocks as well as c) rock which map description allow only to say that they are igneous or metamorphic (type: “undivided”, subtype: “igneous/metamorphic” in attribute table, file “Fig 2, Fig 3\_New coastline 2000\_2020 by glaciers”, dataset: [Kavan and Szczypińska \(2024\)](#), <https://doi.org/10.5281/zenodo.14538245>). Class 3 included only map units where the map does not allow to differentiate between sedimentary and non-sedimentary.

In the next step, all segments were grouped by individual glaciers. If all the segments were in the same rock type class their length was summed, and one feature was created. If segments from a particular glacier represented more than one class they were grouped by classes, resulting in two or three separate features within one glacier.

Retreat areas for individual glaciers from period 2000-2020 were taken from [Kochtitzky and Copland \(2022\)](#) and attributed to the glacier’s new coastline length. In cases where more than one rock type

class was present within one glacier, retreat area was divided proportionally to the summed new coastline length of segments in the classes and attributed to each glacier part.

Finally, NC-RA ratio was calculated for individual glaciers or their parts by dividing the length of segments (in km) by corresponding retreat area (in km<sup>2</sup>).

The Mann-Whitney U test was used to examine the relationship between NC-RA ratio and rock type class. Class 3 was excluded from analysis.

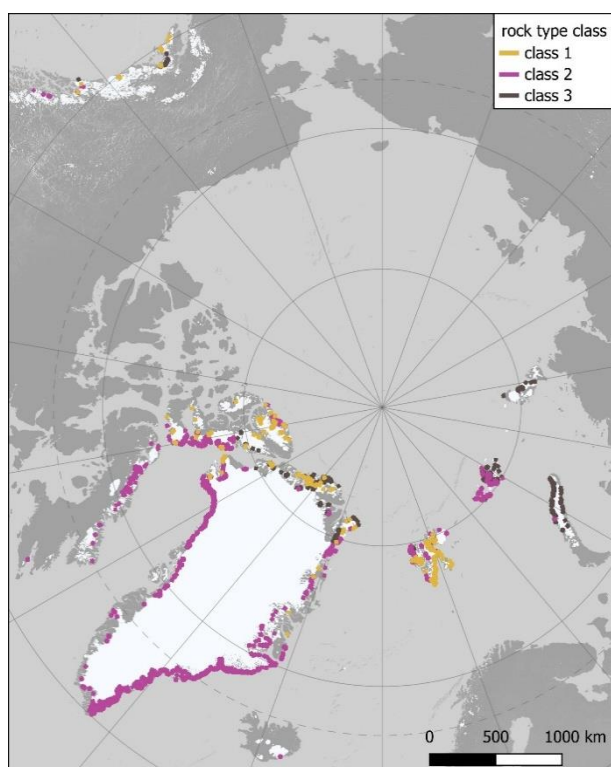


Figure S4. Spatial distribution of rock type classes. Class 1 (sedimentary rocks) displayed in the front.

## Results

Only 85 glaciers out of 1206 included segments from more than one rock type class. The number of glaciers (or glacier parts if more than one rock type class was present) in class 1 is 180, in class 2 is 883 and in class 3 is 228. Figure S4 shows spatial distribution of rock type classes.

NC-RA ratios for individual glaciers range from less than 0,001 km/km<sup>2</sup> to more than 400 km/km<sup>2</sup>. However, after excluding 5% highest and 5% lowest the range is 0.11-15.48 km/km<sup>2</sup>.

The median NC-RA ratio in class 1 is 0.73 km/km<sup>2</sup>, whereas in class 2 it is 1,76 km/km<sup>2</sup>.

The difference in NC-RA ratios between classes proved to be statistically significant even for  $p < 0.01$  ( $U=56333$ ,  $n_1=180$ ,  $n_2=883$ ).

## Discussion

The detected relationship may suggest that rock type in the Arctic affects the value of NC-RA ratio as well as it can be explained by specific spatial distribution of rock type classes.

The mechanisms of rock type's impact on coastline gain effectiveness probably include the fact that valleys in softer rocks tend to be wider than in harder rocks (Bernard et al., 2021). Glacial erosion may also be more efficient in forming straight, less complex slopes (becoming cliffed coastlines after glacier retreat) in softer rocks (e.g. McColl and Davies, 2012; Hall et al. 2013; Brædstrup et al. 2016; Orr et al. 2019). The fact that sedimentary rocks can be widely found in North Greenland and Arctic Canada and are absent in the other parts of Greenland and in Baffin Island may be of great importance for our interpretation. The reason for that is the presence of ice shelves, which we observed to be least effective in new coastline emergence (very large aerial retreat in case of ice shelf collapses and little new coastline).

We are aware that our approach has important limitations. Firstly, it should be noted that the geological map used is in scale 1:500,000. Therefore, it is only a general geological description. Secondly, the formation of only two rock type classes limits the level of detail. Furthermore, the assumption that sedimentary rocks are softer than igneous and metamorphic rocks is not always accurate. Finally, geological characteristics other than rock type (weathering state, fractures, etc.) are

not taken into account here. In spite of that the results are still statistically significant. This suggests that more detailed studies (including e.g. the strength of particular types of rocks mapped or rock type combined with other geological descriptions including fractures and joints) may also yield statistically significant results and provide a better understanding of the character of the relationship and processes involved.

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