COASTAL CLIFF MONITORING - COWBAR NAB, STAITHES, N. YORKSHIRE

August 2018

N Rosser

University of Durham

Prepared for and on behalf of:

Scarborough Borough Council

c/o Robin Siddle

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1. EXECUTIVE SUMMARY

- This report summarizes results from monitoring coastal erosion and cliff retreat at Cowbar Nab, Staithes, over two timescales:
    - Monthly analysis over the period since our last report to RCBC in May 2015. This includes higher-frequency data collected during the 11 months since installation of a permanent monitoring instrument in October 2017,
    - Annual data since start of our monitoring at this site in January 2011.
- The monitoring program is being undertaken for and on behalf of Scarborough Borough Council and Redcar and Cleveland Borough Council.
- This report establishes describes the rate of erosion and highlights features of the changes observed that are pertinent to the management of erosion risk at this site.
- We make recommendations based upon the changes that we have observed to date, and the outcomes from our wider program of coastal erosion monitoring along this coastline.
- In summary, the following tasks have been completed as part of this project and related research since 2011, which are reported below:
  - Monthly high-resolution terrestrial laser scans of the cliff at Cowbar Nab have been undertaken, ongoing since January 2011, from a single position on the foreshore during low tides (Table 1).
  - The development and testing of a new permanent monitoring system has been completed. This generates constant hourly monitoring which has been ongoing since 1 October 2017.
  - Our outputs from our ongoing program of work on the erosion of the N. Yorkshire coast has been compared to the results generated at Cowbar Nab.

2. CHANGES TO THE MONITORING HARDWARE SINCE OCTOBER 2017

- In October 2017 testing was completed on a permanently installed laser scanning system at Cowbar Nab, which provides near real time data on cliff erosion (Figures 1 - 4). The system captures data every hour (Figure 2) and posts the calculated hour by hour erosion to a web-based interface, detailed below. The approach is described in detail in the following doctoral thesis, available online:
    - Williams, J. G. (2017) Insights into Rockfall from Constant 4D Monitoring. Doctoral thesis, Durham University: http://etheses.dur.ac.uk/12172/
- The current set-up has been developed using a basic form of 3D data processing to obtain change that is constantly updated as new scans are collected and archived. Total change over different rolling time periods can be viewed on the following websites:
    - Change over the last month:

      https://community.dur.ac.uk/s.j.waugh/scans/cowbar_monthly_change.html
    - Change over the last week:

      https://community.dur.ac.uk/s.j.waugh/scans/cowbar_weekly_change.html

      Change over the last day:

      https://community.dur.ac.uk/s.j.waugh/scans/cowbar_daily_change.html
    - Change over the last hour:

      https://community.dur.ac.uk/s.j.waugh/scans/cowbar_hourly_change.html
- Note that these websites are best viewed in the most recent version of Google Chrome web browser, and require a high speed internet connection to stream the data.
- The view of the data is 3D and interactive. A menu is available in the top left of the screen, which contains a series of options to take measurements, and to change the view settings. At present the change data is shown on a colour scale that spans the range of the observed changes in the given time period. Blue indicates no change, and red indicates maximum change. At present, the maximum change is attributed with a quantity in the publically available display of the data to aid easy visualization of the change data.
- Currently work is ongoing on the implementation of a more advanced coding for analysis of the change collected by this system, based upon comparable work at East Cliff, Whitby. This automates the extraction of individual rockfall characteristics at 1-hour increments to derive an erosion rate through time. We anticipate a fully interactive display based upon this work (see: Wiliams, 2017) to be running in late summer 2018 after beta testing is complete.
- To present monthly foreshore surveys have continued to maintain data continuity and comparability from 2011. We report below the data from the fixed monitoring system in parallel to that collection from the foreshore.

Fixed monitoring system:

Figure 1. Completed installation of the fixed monitoring system at Cowbar Nab. In the foreshore is the solar power enclosure, providing off-grid power to the monitoring system. The larger green shelter houses the power control system, and the small green enclosure the monitoring instrument.

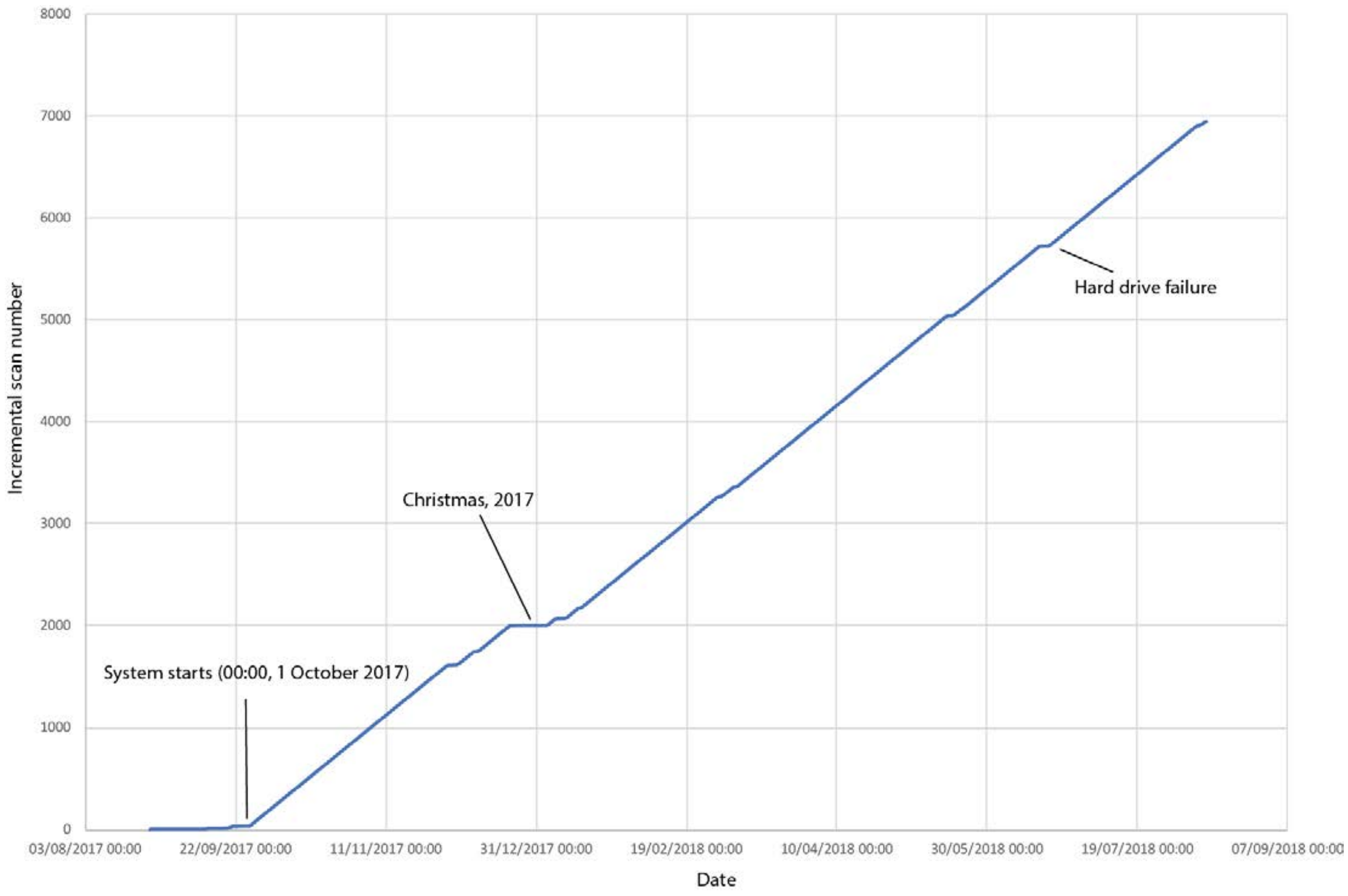


Figure 2. Hourly scan rate record, from start of systematic monitoring (1 October 2017 @ 00:00), with interruptions annotated, included snow cover on the solar array over Christmas 2017, and a hard drive failure within the monitoring instrument in June 2018. Monitoring has otherwise been continuous with data loss only occurring during poor weather conditions, such as fog obscuring the scanner.

Figure 3. Example of data captured from the cliff top scanner. White areas are occluded (invisible from the scanner position).

Figure 4. View of the instrument cabinet at Cowbar, showing the view onto the Nab.

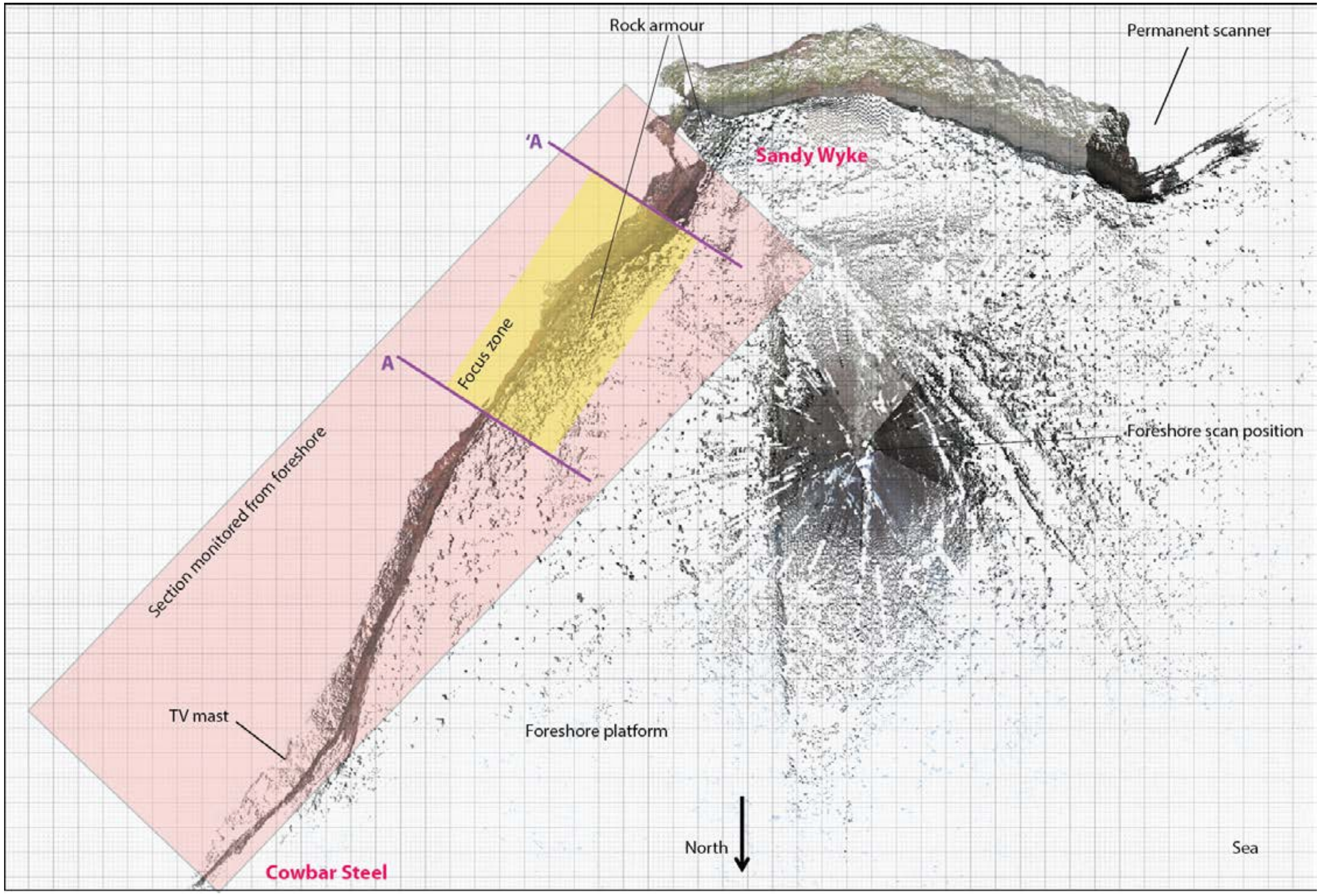
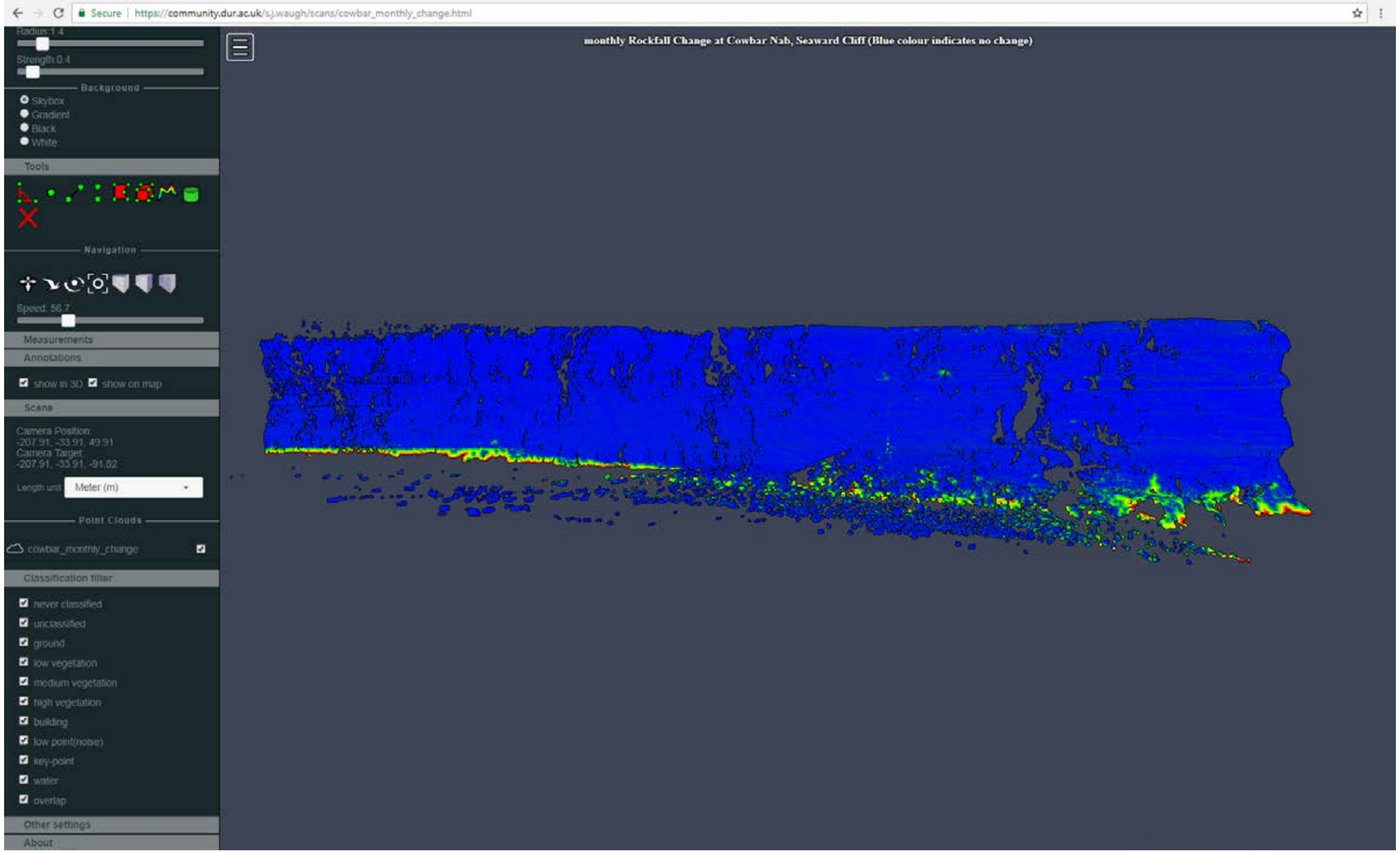


Figure 5. Map view based upon point cloud obtained from a foreshore scan, showing the areas used in the calculation of erosion rates. Pink area shows the full study site, and the yellow area shows the 'focus zone' discussed below.



https://community.dur.ac.uk/s.j.waugh/scans/cowbar_monthly_change.html

monthly Rockfall Change at Cowbar Nab, Seaward Cliff (Blue colour indicates no change)

Radius: 1.4
Strength: 0.4

● Skybox
○ Gradient
○ Black
○ White

Speed: 56.7

☑ show in 3D ☑ show on map

Camera Position:
-207.91, -33.91, 49.91
Camera Target:
-207.91, -33.91, -91.82

Length unit: Meter (m)

cowbar_monthly_change ☑

☑ never classified
☑ unclassified
☑ ground
☑ low vegetation
☑ medium vegetation
☑ high vegetation
☑ building
☑ low point(noise)
☑ key-point
☑ water
☑ overlap

Figure 6. Example of the online display of the live erosion data, here showing 1-month of rolling change calculated from hourly scans (see: https://community.dur.ac.uk/s.j.waugh/scans/cowbar_monthly_change.html). Blue colours indicate no discernable change, and increasingly hot colours show erosion of the cliff face. The controls on the left hand menu allow manipulation of the data, and measurements to be taken.

3. CHANGES TO THE CALCULATION OF EROSION RATES

- In our approach we monitor the entire side of Cowbar Nab, from Sandy Wyke to Cowbar Steel (see Figure 5). We note from the 7.6-years of monitoring the emergence of a consistent pattern of more intense erosion in the section of the Nab immediately beneath the Lane and Cottages, as compared to the wider extent both to the east, and to the west of this central section, labeled as 'focus zone' in Figure 5.

- A consequence of this relative intensity of erosion is that averaged rates for the whole of the Nab are lower than if they were calculated just for the 'focus zone', immediately below Cowbar Lane only. A clear example of this is shown in Figure Appendix 1.1, whereby the local erosion rate at or immediately around the observed rockfall is higher than the spatially averaged erosion rate for the whole monitored section. We therefore revisit the basis for assessing erosion rates at this site.

- The calculation of erosion rates is obtained by undertaking successive surveys using 3D laser scanners positioned either on the foreshore or on the cliff top. Data from subsequent surveys are subtracted to derive the change, which at these cliffs occurs predominantly through rockfall. The total volume of the rockfalls within the monitoring period is calculated, and the average erosion rate is obtained by dividing the total rockfall volume by the total monitored area. The erosion rate is therefore a direct function of:

    - The <u>extent of the monitored area</u>. At present this is the seaward cliff face of Cowbar Nab, from Sandy Wyke to Cowbar Steel. Note that the precise area monitored changes in each survey due to the state of the tide, data coverage and the scanner position.

    - The number of rockfalls and <u>total volume observed</u>, which is a function of the frequency of monitoring. Importantly, the more frequent the monitoring, the more rockfall are observed, albeit of a smaller individual volume (see: Williams et al., 2018).

    - The <u>precision of measurement of rockfall volume</u>. Where most rockfall are small, errors in volumes obtained from high frequency monitoring can be high.

- It is widely understood that to obtain a reliable and representative erosion rate, the area monitored needs to be sufficiently extensive such that the results are not dominated by large but infrequent rockfall. For example, it is not feasible to obtain a *realistic* whole cliff erosion rate from only monitoring a 1 m^2 section. Without prior knowledge of any local systematic variability in rockfall behavior (e.g. a concentration of erosion in a particular area), long-term erosion rates for the site are therefore best obtained from wide area monitoring, which here has been the entire seaward cliff of Cowbar Nab.

- After 7.6 years of monitoring, the monitoring data is now of sufficient length to assess the relative rates of erosion within the wider monitored site, and so enables us to appraise whether the area over which we calculate erosion is suitable. Our assessment of rockfall since 2011 shows a concentration of erosion on the cliff face between A and A' as indicated in Figure 7 and in Figure 5. This pattern is, at least at present and during the last 7.6 years, quite different to relatively low rates of erosion outside of this area, further east and west.

- Below, we calculate and present erosion rates for both the whole monitored area, as in previous reports, but also erosion rates for the 'focus zone' between A and A' in Figure 7. Whilst these rates calculated over a smaller area are more locally representative, they will be more variable (stochastic) through time. It is important to note that this reduction in area used to calculate erosion rate will result in an increase in the apparent observed erosion rate for this smaller cliff section, but advantageously this brings the erosion rate calculation closer inline with the measured depth of retreat reported both previously, and in the present report in Figures 8 & 10 below.

4. MONITORING RESULTS

a. Results: May 2015 – October 2017 - August 2018

We summarise the erosion rates between May 2015 and August 2018, presented in detail in Table 1 and Figures 7 – 10, which includes higher-frequency monitoring from October 2017. We summarise this on a monthly basis for comparability:

- A total volume loss of 2,728.75 m^3 in 55,642 discrete rockfall events occurred during this 38 month period.

- The area averaged rate of retreat observed in the period May 2015 to August 2018 for the whole site was 0.12 x 10^{-3} myr^{-1}.

- The modeled rate of retreat in the period May 2015 and August 2018 for the whole site was 0.06 x 10^{-3} myr^{-1}.

- The area averaged rate of retreat observed in the period May 2015 to August 2018 for the focus zone was 0.116 myr^{-1}.

- The lowest monthly volume of rockfall was observed in January 2017 (0.05 m^3). The highest monthly volume of rockfall occurred in May 2016 (702.23 m^3) (see: Table 1 and Appendix 1). The maximum depth (relative to the cliff face) of any single rockfall observed into the cliff face during this period was 5.8 m in May 2016 (Figure 9 and 10, and Appendix 1).

- We observe several sequences of events, whereby rockfall in successive months and years appear linked. This includes:

    - Upward propagation of rockfall, initiated by wave quarrying of the cliff toe and subsequent failure of the overhanging cliff mass above to leave a near-planar, near-vertical cliff face remaining.

    - Failure of convex sections of the cliff face, to leave a near-vertical cliff face remaining.

    - Lateral across cliff failure migration, whereby rockfall scars coaslesce into cross-cliff arch structures, which are inherently more stable, and are commonly bounded above by more massive rock beds. We note this behavior within the focus zone described above, most notably immediately above the rock armour.

    - We observe that compared to immediately preceeding years, data collected with the fixed monitoring system since October 2017 (Figures 9 & 10) has been relatively quiet. A series are failures have occurred, but these have tended to be isolated, rather than contiguous upon the cliff face. Recent failures in the winter have been at the cliff toe, incidative of marine action, and subsequently in the summer months high up on the rock face. None of these failures has influenced the cliff top and within themselves indicate no pattern of wider instability.

- One observation of note is the quarrying of the cliff toe immediately to the west of the rock armour (right in Figures 7 - 11), which has led to the undercutting off the cliff face above. This is also captured in our analysis of Profile 3, discussed below.
- We note some upwards propagation of this zone of failure. We note also that this failure sits below a section of coastline where the fence line and road are set further back, so if this failure were to develop upcliff, based upon the depth of previous failures, it would be unlikely to threaten any assets on the cliff top.
- We note 2 zones of failure in the glacial till in December 2016. The morphology of these failures suggests a shallow translational sliding mechanism, removing approximately 3 m (width) by 8 m (height) of turf cover on the till cliff slope. After these failures, we note only minor activity in these areas, beyond seasonal changes in vegetation. It is likely that these slumps occurred during or immediately after intense rainfall.
- The only significant loss of cliff top material within the period March 2015 and August 2018 was related to the rockfall in May 2017, reported previously to RCBC in mid May 2017 (see Appendix 1). This area of the cliff face has subsequently remained stable, but is now steeper (near-vertical) with the top of the rock cliff closer to the road, and ca. 1 m from the cliff top fenceline.
- Besides this event, there was no significant loss of cliff top rock observed since May 2015, despite continued undercutting of the cliff toe below. The upward propagation of the areas of failure is highly likely to follow as the cliff will tend to retain a near-vertical profile.
- The spatial pattern of erosion is commensurate with marine driven erosion at the toe of the cliff, in addition to the continued failure of previously active areas of the cliff expanding further. Work on the nature of this process, included outputs from monitoring at Cowbar has been published in Rosser et al., (2013) on cliffs of similar geological structure and environment, and the various research theses referred to in the reference list provided.

b. Results: January 2011 – August 2018

The long-term (January 2011 to August 2018) annualized erosion rates are as follows for the 92 months of monitoring at this site to date:

- 92 month area averaged erosion rate for the whole site is 0.68 x 10^{-3} myr^{-1}. This is based on observed rockfall alone.

- 92 month modeled erosion rate for the whole site is 0.606 x 10^{-3} myr^{-1}. This rate considers the full range of possible rockfall sizes at this site, and will stabilize over time as a more complete range of event sizes is recorded. This approach overcomes the limitations of monitoring only a small area / non representative sample, during a limited time period (see: Barlow *et al.*, (2012) for methodology).

- 93 month area averaged erosion rate for the focus zone is 0.08 myr^{-1}. This rate is based purely on the rockfalls observed at the site using the laser monitoring.

- 92 month modeled erosion rate for the focus zone is 0.08 myr^{-1}. This rate considers the full range of possible rockfall sizes at this site, and will stabilize over time as a more complete range of event sizes is recorded. This approach overcomes the limitations of monitoring only a small area / non representative sample, during a limited time period (see: Barlow *et al.*, (2012), and Benjamin et al., 2017).

- Since the start of monitoring in 2011 we observe a total of 3,954.51 m^3 of rockfall, sourced from 120,320 discrete rockfall events identified from monthly sequential monitoring. This total volume of rockfall is equivalent to a 15.8 m cube. Rockfall at this site adhere to a power law volume frequency distribution. This means that the majority of rockfall are small (ca. 2.5 x 10^{-4} m^3 or smaller) with a descreasing frequency of increasingly large events. As such, whilst the number of rockfall observed is high, their individual volume and the erosion that the majority accrue remains small.

- On average over 92 months, 1,322 discrete rockfall events occur at this site each month, in rockfall volumes > 2.5 x 10^{-4} m^3.

- Over 92 months, the average monthly volume of rockfall is 43.46 m^3, equating to 0.189 m^3 per month per metre of coastline, and equivalent to a cube of dimensions 0.574 m from each metre of coastline in each month.

- Between May 2015 and August 2018, the area averaged erosion rates for the full site were higher than in the years between January 2011 and May 2015 (Table 1). This increase is attributed to the occurrence of a small number of larger rockfall (e.g. May 2016), in addition to several major winter storm periods which were observed to result in both increased rates of background rockfall activity (e.g. Storm Desmond, 3 – 8th December 2015), and substantial direct responses to these events themselves.

- The modeled erosion rate for the whole site, and for the focused site, continues to converge to a stable longer-term average (Table 1). This reflects the tendency to capture a more complete rockfall volume frequency distribution of all possible rockfall volumes within a longer period of monitoring. This gives more more confidence in the annualized erosion rates as a function of the convergence of these two methods.

- The rates of erosion observed at this site within each month remain heavily influenced by a low number (commonly < 3 in any given month) of larger (> 1 to 10 m^3) rockfall events. Where no such event occurs in any given month, the retreat rates are accordingly low, as seen during the majority of this monitoring period.

- As a result, the potential for retreat at any point on the coast remains best predicted with a detailed structural assessment of the rock mass and change experience at that specific location, rather than wider area, long term erosion rates.

- Over the 7.6 years of monitoring we continuously observe the development of vertically propagating rockfall scars that evolve from one year to the next. This process is initiated by wave action at the cliff toe, which destabilses the cliff toe above, tending to result in the failure of convex sections of the cliff face. We previously noted the presence of two areas of failure on either side of the rock armour, which we suggested were likely to coalesce in the future via further rockfall. We are continuing to see this develop to present.

- The monthly volume of rockfall for this section of cliff is slightly lower than that observed elsewhere along this coastline (see: Benjamin, 2018), most likely due to the relatively low (< 30 m) cliff height as compared to the coastline both east and west of this site. Differences in retreat rates per unit area between this site and other sites monitored elsewhere on this coastline remain comparable and broadly in proportion to the cliff height / available rockfall source area.

- Based upon this data, there is no indication that the erosion of the cliff at Cowbar is accelerating or deviating away from behavior observed at this site previously. The variations in rates of erosion reported here represents variability widely observed on similar cliffs, and should not taken to infer increasing or decreasing stability. This monitoring period, as in the previous period, however demonstrates the possibility for continued larger-scale rockfall at this site and highlights a need to plan for mitigation at this site moving forward.

c. Analysis of profile form change

- Slope profiles have been extracted from the laser scan data through the cliff. Profile locations are provided in Figure 7, and profile change through time on an annual basis is provided in Figure 11.

- Profile 1 underwent significant change in May 2016 due to the large rockfall discussed above, and illustrated in Appendix 1. We note that this rockfall resulted in the loss of a previously overhanging section of the cliff face, removing rock to the cliff top.

- We note that Profile 2, positioned immediately above the rock amour, has a convex form, with an overhang of up to 4 m. Notably this is very similar to the cliff form at Profile 1 prior to collapse. Whilst the exact line of this profile has undergone little change between May 2015 and August 2018, we note in Figure 9 and 10, rockfalls in the zone immediately adjacent to the most protruding section of this overhang recently, which are likely to continue to propagate laterally over coming months. As a result, whilst this profile has remained little changed in this monitoring period, we anticipate that the rock above this section will fail next. The timing of this remains unknown, and our data to date shows no sign that this is imminent. Importantly, based on the style of previous failures of this type at this location, the rockfall will likely remove the overhang, rather than retreat the cliff edge back substantially.

- Profile 3 shows loss of material close to high water level at the cliff toe. We anticipate that this area of failure will develop over coming months, to eventually over-steepen and collapse the cliff face above. The cliff line at this point is some 5.5 m seaward of the fenceline, and so based on the style of previous failures, this would be unlikely to impact upon assets at the cliff top.

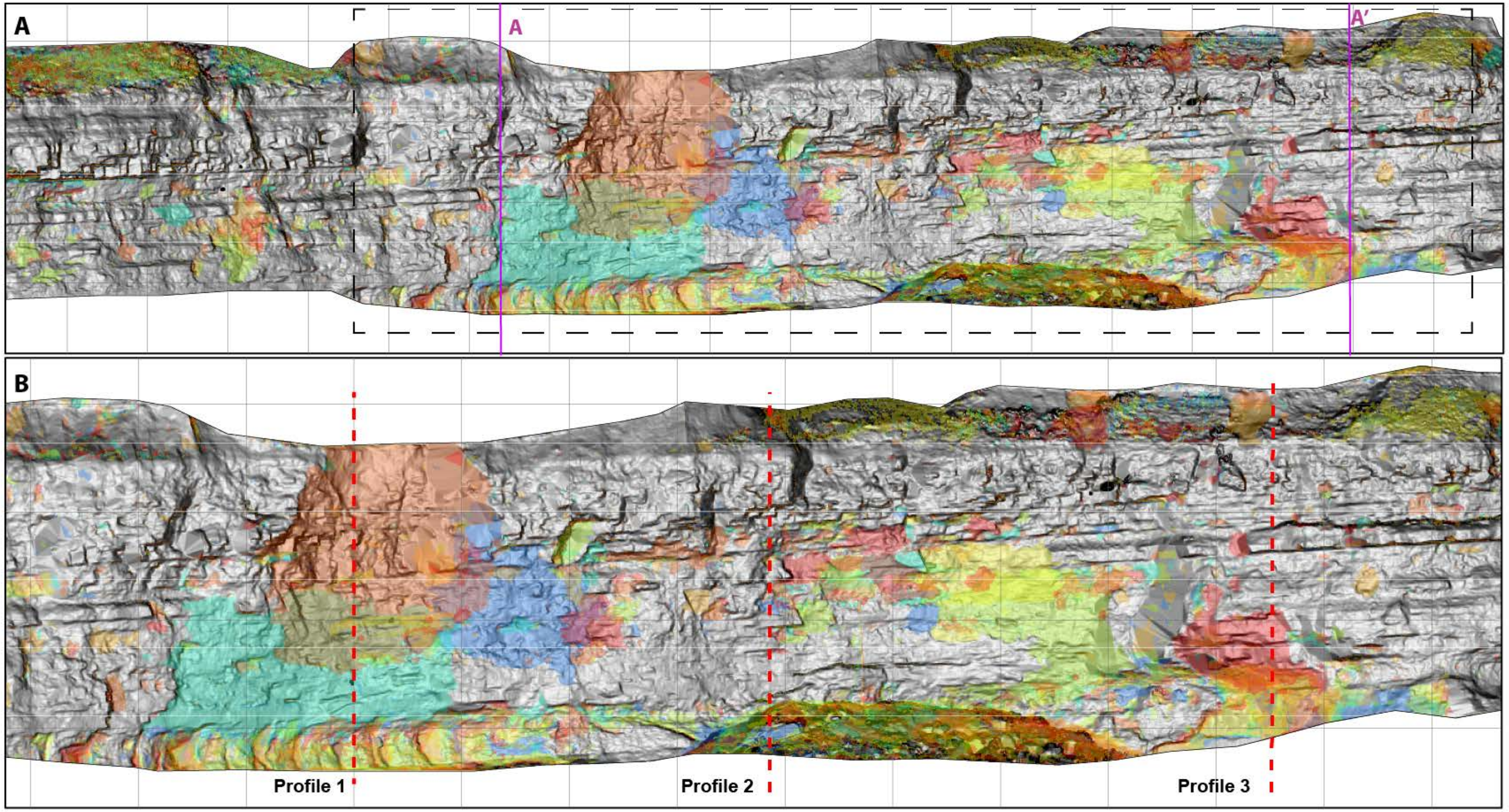


Figure 7. Monitored erosion at Cowbar Nab between January 2011 and August 2018. **(A)** shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point on the foreshore at low tide. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the colours show areas of rockfall since 2011 coloured by year. The grid interval is 10 m on both horizontal and vertical axis. The black dashed square delimits the extent of the area shown in B. Location of profiles in Figure 11 is detailed by red dashed lines. Purple lines show bounds of 'focus zone' refered to in text. **(B)** shows a close up view of the cliff directly beneath Cowbar Lane and directly above the rock armour.

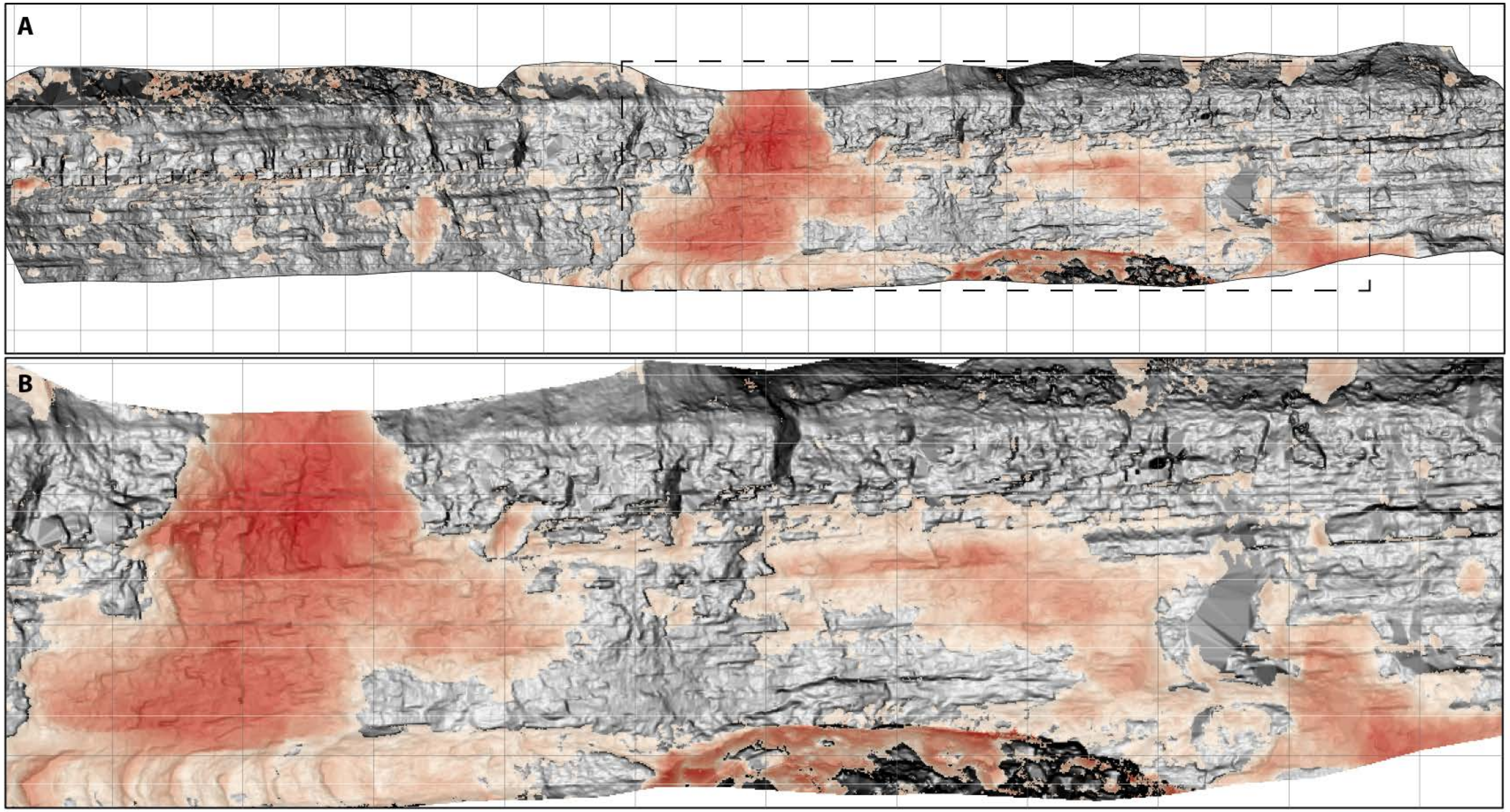


Figure 8. Monitored erosion at Cowbar Nab between January 2011 and August 2017, showing depth of erosion (increasing depths are hotter colours). **(A)** shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the change is coloured by depth relative to the cliff, ranging from 0 to 5.8 m in geometrically increasing intervals. The grid interval is 10 m on both the horizontal and vertical axis. The dashed box delimits the extent of the area shown in B. **(B)** shows a close up view of the cliff directly beneath Cowbar Lane and directly above the rock armour.

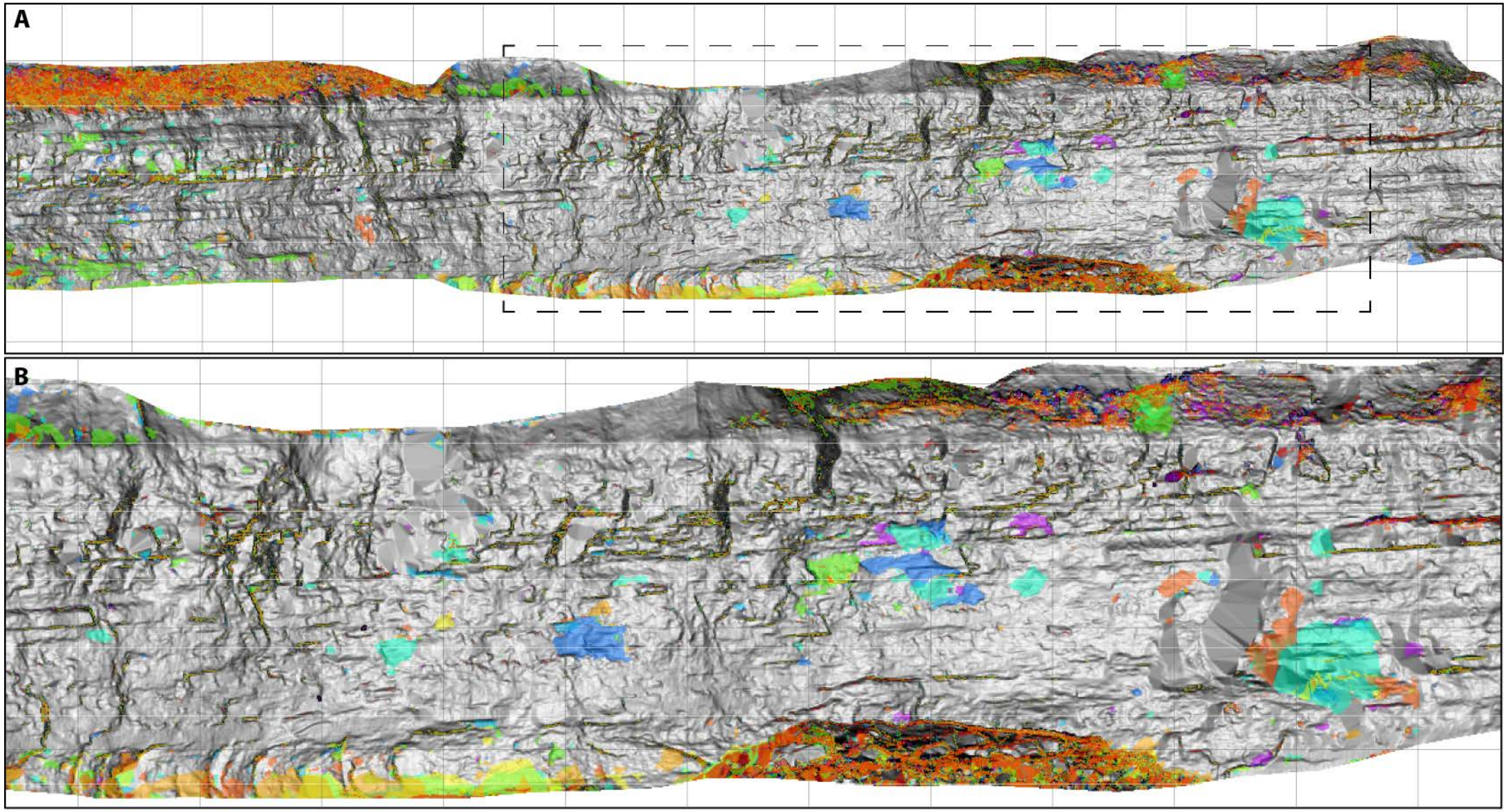


Figure 9. Monitored erosion at Cowbar Nab between October 2017 and August 2018, showing areas of failure for each monthly monitoring survey. **(A)** shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the change is coloured by month of failure. The grid interval is 10 m in both horizontal and vertical axes. The dashed box delimits the extent of the area shown in B. **(B)** shows a close up view of the cliff directly beneath Cowbar Lane and directly above the rock armour.

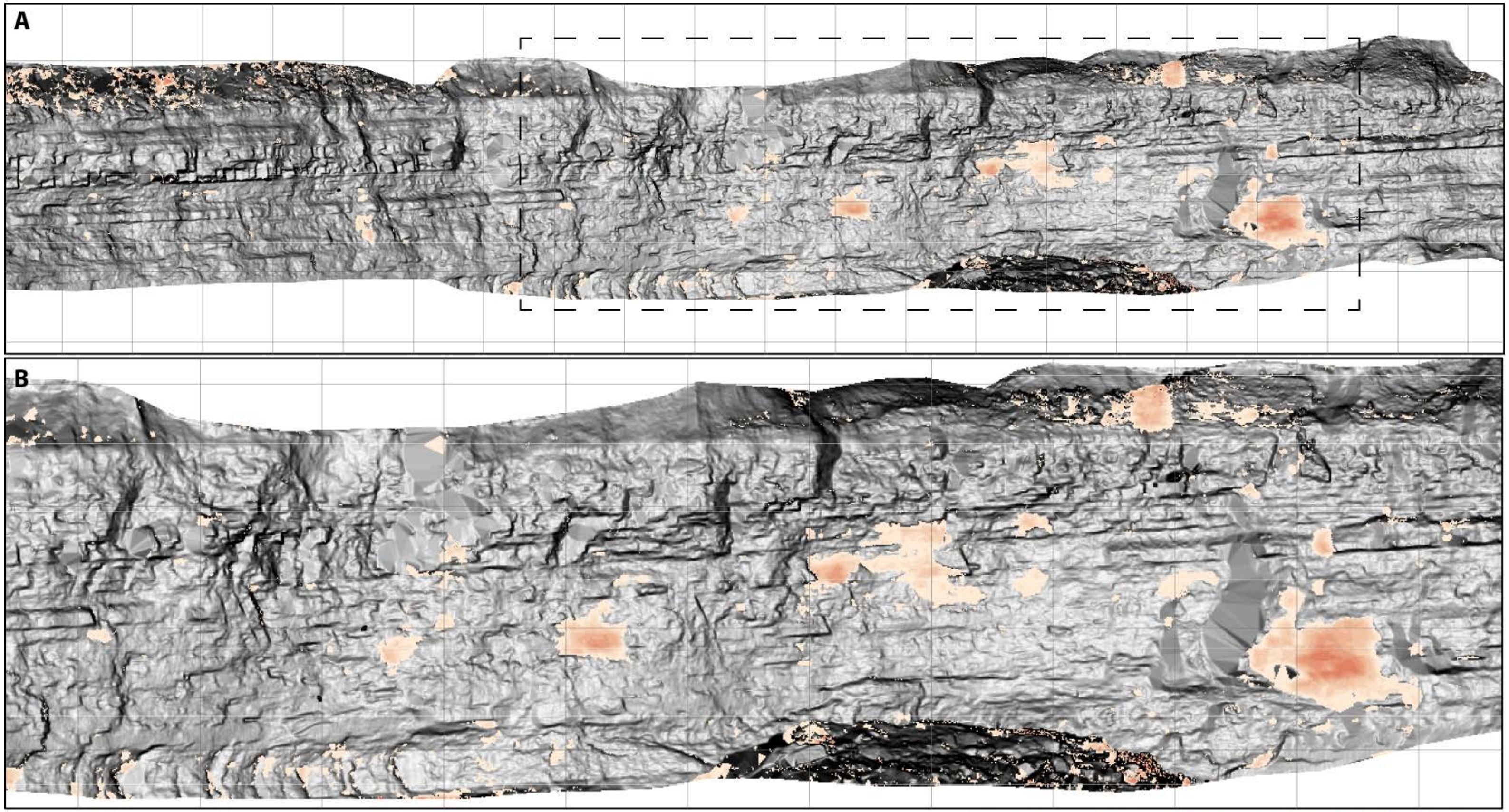


Figure 10. Total depths of monitored erosion at Cowbar Nab between January 2011 and August 2018, showing depth of erosion (increasing depths are hotter colours). **(A)** shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the change is coloured by depth relative to the cliff, ranging from 0 to 5.8 m in geometrically increasing intervals. The grid interval is 10 m in both horizontal and vertical axes. The dashed box delimits the extent of the area shown in B. **(B)** shows a close up view of the cliff directly beneath Cowbar Lane and directly above the rock armour.

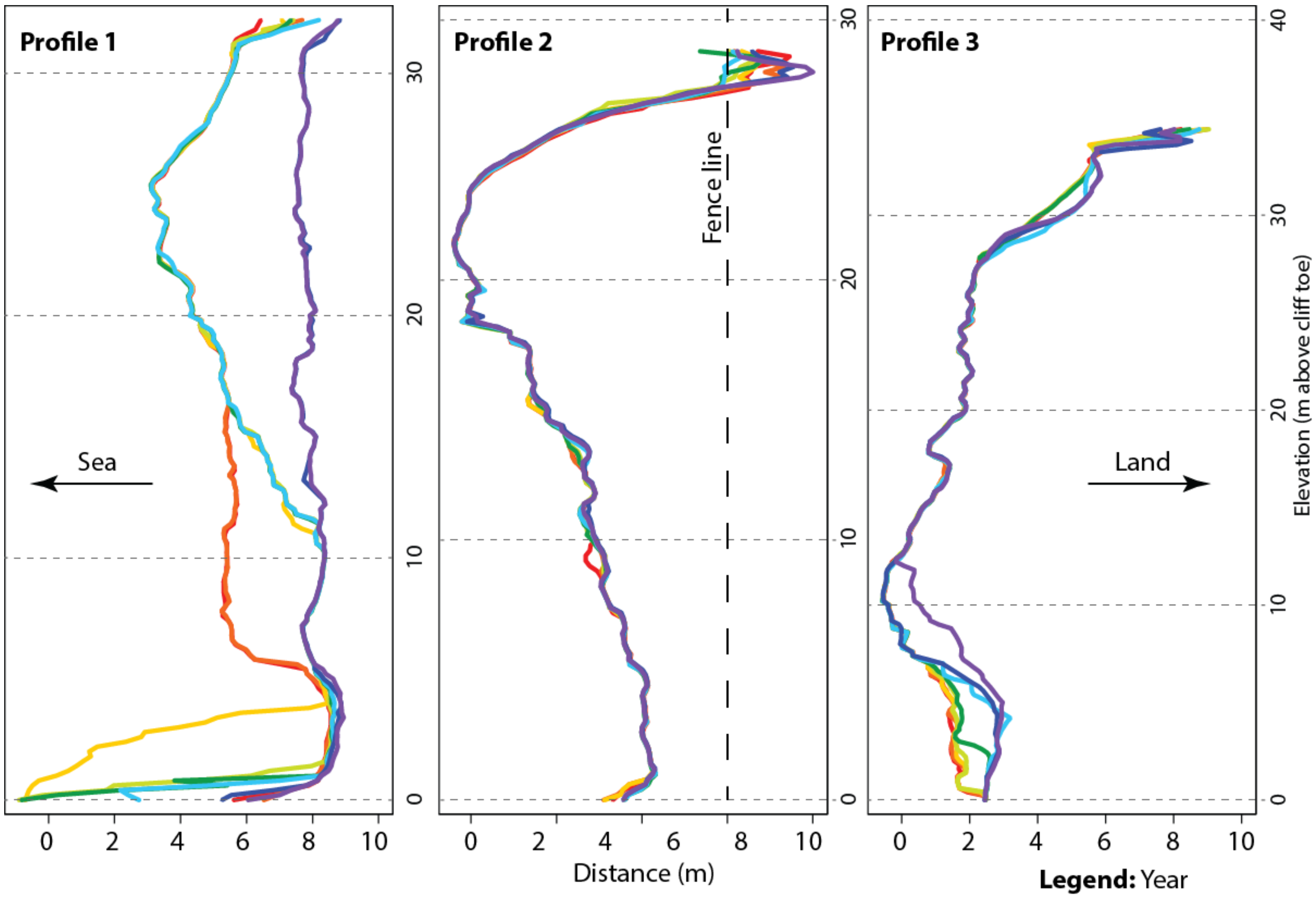


Figure 11. Cliff profiles (locations shown in Figure 1). Profile topography is taken from years 2011 through 2018. Horizontal distances are in units of m from a arbitrary datum in front of the cliff toe. Retreat of the cliff is from left to right. Note that the vertical scale is different for each profile.

5. High-frequency monitoring:

The fixed scanner at Cowbar enables more information on the size, location and timing of rockfall to be derived, that describe when rockfall are more likely to occur, with information to an hourly level of detail.

Whilst 11 months of data is not sufficient to draw conclusions, based upon data from Cowbar and that also collected at East Cliff, Whitby, we observe that:

- An increase in monitoring frequency to 1-hour intervals reveals a 10^3 increase in the number of rock blocks observed to fall from the cliff. This is because at 1-month intervals the rockfalls that are measured as single larger rockfall are actually a larger number of smaller neighbouring events. The absolute frequency of rockfall is therefore higher than monthly monitoring would suggest.
- A consequence of higher frequency monitoring is that the average size of rockfalls observed is 10^2 smaller at 1-hour intervals as compared to 1-month intervals. This is again because over 1-month intervals multiple smaller rockfall are observed as a single larger event. Whilst the mean size observed reduces, it remains the case that a rockfall of any size can occur.
- On average, throughout the year, small rockfall appear to occur at random, and there is no period when rockfall frequency reduces to zero.
- Large rockfalls have been observed to tend to coincide with high tides, although can occur at any time.
- The rate of rockfalls is steady through the Spring and Summer, but experiences a step-change increase at the start of Autumn, which is sustained throughout the winter.
- Single large storms in the winter can account for >15% of the total rockfall volumes experienced during the year.
- On average, we observe a steady rise in rockfall rate (ca. 10%) through the day from dawn to dusk.
- A spike in rockfall frequency is observed at sunrise, and but most notably at sunset.
- These findings are considered in greater detail in Willaims et al., (2018) and Williams (2017).

Table 1. Combined erosion rates for January 2011 – August 2018 for the monitored cliff section. Rates are derived using the methods outlined in the Appendix.

Year	Month	Month	Year	Survey date	Survey epoch length (days)	Running total of days	Number of rockfalls	Total volume of rockfalls (m3)	Area average erosion rate (x 10 -3 myr-1)	m/f modelled erosion rate (x 10-3 myr-1)	Monthly average erosion rates (m yr-1)	1 year average of monthly average erosion rates (m yr-1)	Focus area erosion rate (m yr-1)	Focus area erosion rate (m yr-1)
1	1	January	2011	40557	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	2	February	2011	40592	35	35	990	31.69	2.770	0.023	0.0028		0.051	
	3	March	2011	40623	31	66	969	31.00	2.710	2.816	0.0027		0.051	
	4	April	2011	40661	38	104	1036	33.15	2.900	1.716	0.0029		0.054	
	5	May	2011	40683	22	126	4	0.13	0.010	0.000	0.0000		0.000	
	6	June	2011	40711	28	154	21	0.68	0.060	0.022	0.0001		0.001	

	7	July	2011	40745	34	188	660	21.11	1.850	0.484	0.0019		0.034	
	8	August	2011	40780	35	223	560	17.93	1.570	2.684	0.0016		0.030	
	9	September	2011	40813	33	256	972	31.11	2.720	4.554	0.0027		0.053	
	10	October	2011	40837	24	280	802	25.66	2.240	4.642	0.0022		0.042	
	11	November	2011	40864	27	307	708	22.65	1.980	3.850	0.0020		0.038	
	12	December	2011	40896	32	339	207	6.62	0.580	0.176	0.0006	0.0018	0.011	0.033
2	13	January	2012	40925	29	368	609	19.48	1.700	1.760	0.0017		0.033	
	14	February	2012	40962	37	405	1323	42.33	3.700	2.816	0.0037		0.069	
	15	March	2012	40994	32	437	1108	35.45	3.100	2.860	0.0031		0.057	
	16	April	2012	41017	23	460	2074	19.39	1.620	1.480	0.0016		0.031	
	17	May	2012	41038	21	481	1346	24.51	2.950	2.370	0.0030		0.042	
	18	June	2012	41079	41	522	356	3.09	0.360	0.220	0.0004		0.005	
	19	July	2012	41104	25	547	101	2.91	0.330	0.210	0.0003		0.005	
	20	August	2012	41123	19	566	334	2.54	0.390	0.210	0.0004		0.004	
	21	September	2012	41160	37	603	598	7.79	0.880	0.170	0.0009		0.013	
	22	October	2012	41185	25	628	5312	11.15	0.570	0.350	0.0006		0.018	
	23	November	2012	41228	43	671	3231	7.32	0.630	0.360	0.0006		0.013	
	24	December	2012	41256	28	699	227	12.23	0.650	0.450	0.0007	0.0014	0.021	0.025
3	25	January	2013	41280	24	723	2891	2.85	0.510	0.140	0.0005		0.005	
	26	February	2013	41316	36	759	4379	20.24	5.290	1.090	0.0053		0.035	
	27	March	2013	41345	29	788	946	14.93	2.600	2.010	0.0026		0.025	
	28	April	2013	41389	44	832	160	366.76	4.979	1.500	0.0050		0.625	
	29	May	2013	41417	28	860	559	1.03	0.014	2.459	0.0000		0.002	
	30	June	2013	41450	33	893	251	7.23	0.098	0.234	0.0001		0.013	
	31	July	2013	41477	27	920	553	8.52	0.116	0.250	0.0001		0.014	
	32	August	2013	41506	29	949	349	6.83	0.093	0.229	0.0001		0.011	

	33	September	2013	41534	28	977	463	40.34	0.548	0.215	0.0005		0.065	
	34	October	2013	41568	34	1011	641	0.28	0.004	0.384	0.0000		0.000	
	35	November	2013	41596	28	1039	409	7.38	0.100	0.418	0.0001		0.013	
	36	December	2013	41611	15	1054	349	6.86	0.093	0.534	0.0001	0.0013	0.012	0.074
4	37	January	2014	41656	45	1099	517	7.04	0.096	0.205	0.0001		0.012	
	38	February	2014	41688	32	1131	309	1.74	0.024	1.127	0.0000		0.003	
	39	March	2014	41713	25	1156	255	4.60	0.062	2.096	0.0001		0.008	
	40	April	2014	41745	32	1188	2205	16.93	0.274	0.027	0.0003		0.028	
	41	May	2014	41773	28	1216	2245	103.93	1.683	1.265	0.0017		0.170	
	42	June	2014	41808	35	1251	1436	57.84	0.936	0.229	0.0009		0.101	
	43	July	2014	41834	26	1277	1449	10.94	0.177	0.169	0.0002		0.018	
	44	August	2014	41863	29	1306	1401	9.89	0.160	0.072	0.0002		0.017	
	45	September	2014	41892	29	1335	1470	7.65	0.124	0.074	0.0001		0.013	
	46	October	2014	41921	29	1364	3234	20.26	0.328	0.320	0.0003		0.032	
	47	November	2014	41949	28	1392	813	3.99	0.065	0.040	0.0001		0.007	
	48	December	2014	41978	29	1421	2427	14.55	0.236	0.096	0.0002	0.0004	0.024	0.038
5	49	January	2015	42025	47	1468	1944	9.65	0.156	0.103	0.0002		0.015	
	50	February	2015	42053	28	1496	983	4.88	0.079	0.067	0.0001		0.008	
	51	March	2015	42087	34	1530	727	4.24	0.069	0.031	0.0001		0.007	
	52	April	2015	42115	28	1558	3962	35.36	0.572	0.353	0.0006		0.060	
	53	May	2015	42143	28	1586	3802	19.11	0.309	0.014	0.0003		0.031	
	54	June	2015	42170	27	1613	1976	6.89	0.172	0.189	0.0002		0.012	
	55	July	2015	42195	25	1638	281	103.59	1.185	0.721	0.0012		0.170	
	56	August	2015	42227	32	1670	1411	21.97	0.363	0.004	0.0004		0.038	
	57	September	2015	42256	29	1699	758	1.91	0.017	0.068	0.0000		0.003	
	58	October	2015	42282	26	1725	522	5.65	0.097	0.008	0.0001		0.009	

	59	November	2015	42313	31	1756	228	5.31	0.066	0.010	0.0001		0.009	
	60	December	2015	42344	31	1787	2069	15.16	0.261	0.046	0.0003	0.0003	0.026	0.034
6	61	January	2016	42373	29	1816	437	0.30	0.003	0.032	0.0000		0.001	
	62	February	2016	42406	33	1849	506	0.47	0.013	0.001	0.0000		0.001	
	63	March	2016	42437	31	1880	1873	7.53	0.050	0.072	0.0000		0.013	
	64	April	2016	42471	34	1914	863	105.26	0.033	0.010	0.0000		0.168	
	65	May	2016	42501	30	1944	364	702.23	0.042	0.013	0.0000		1.191	
	66	June	2016	42533	32	1976	1747	7.18	0.481	0.076	0.0005		0.012	
	67	July	2016	42561	28	2004	1860	7.66	0.237	0.012	0.0002		0.013	
	68	August	2016	42597	36	2040	829	19.74	0.223	0.001	0.0002		0.032	
	69	September	2016	42599	2	2042	548	0.11	0.003	0.063	0.0000		0.000	
	70	October	2016	42653	54	2096	83	0.81	0.056	0.007	0.0001		0.001	
	71	November	2016	42676	23	2119	194	0.44	0.009	0.001	0.0000		0.001	
	72	December	2016	42707	31	2150	1309	4.56	0.172	0.035	0.0002	0.0001	0.007	0.130
7	73	January	2017	42740	33	2183	70	0.05	0.001	0.019	0.0000		0.000	
	74	February	2017	42773	33	2216	231	0.44	0.012	0.000	0.0000		0.001	
	75	March	2017	42802	29	2245	1190	4.83	0.048	0.071	0.0000		0.008	
	76	April	2017	42834	32	2277	500	90.33	0.006	0.007	0.0000		0.147	
	77	May	2017	42865	31	2308	175	614.22	0.300	0.007	0.0003		1.054	
	78	June	2017	42897	32	2340	358	1.15	0.356	0.035	0.0004		0.002	
	79	July	2017	42932	35	2375	1502	4.65	0.001	0.000	0.0000		0.007	
	80	August	2017	42962	30	2405	319	10.54	0.183	0.001	0.0002		0.018	
	81	September	2017	42988	26	2431	239	0.05	0.002	0.001	0.0000		0.000	
	82	October	2017	43009	21	2452	69	0.53	0.041	0.006	0.0000		0.001	
	83	November	2017	43040	31	2483	3546	89.65	0.010	0.057	0.0000		0.153	
	84	December	2017	43070	30	2513	4375	133.70	0.043	0.116	0.0000	0.0001	0.231	0.148

8	85	January	2018	43101	31	2544	3668	141.32	0.027	0.071	0.0000		0.238	
	86	February	2018	43132	31	2575	3813	107.46	0.017	0.176	0.0000		0.176	
	87	March	2018	43160	28	2603	4619	62.80	0.007	0.093	0.0000		0.108	
	88	April	2018	43191	31	2634	3649	110.92	0.006	0.027	0.0000		0.184	
	89	May	2018	43221	30	2664	2169	184.71	0.062	0.142	0.0001		0.307	
	90	June	2018	43252	31	2695	2959	37.02	0.010	0.009	0.0000		0.061	
	91	July	2018	43282	30	2725	2081	80.61	0.010	0.093	0.0000		0.128	
	92	August	2018	43313	31	2756	2252	36.99	0.004	0.057	0.0000	0.0000	0.064	0.158
						Running total of days	**Number of rockfalls**	**Total volume of rockfalls (m3), total monitored area**	**Area average erosion rate (x 10 -3 myr-1)**	**m/f modelled erosion rate (x 10-3 myr-1)**	**Monthly average erosion rates (m yr-1)**	**1 year average of monthly average erosion rates (m yr-1)**	**Focus area erosion rate (monthly, m yr-1)**	**Focus area erosion rate (annual, m yr-1)**
				Total		2756	120320	3954.51	n/a	n/a	n/a	n/a	n/a	n/a
				Average		n/a	1322	43.46	0.680	0.606	0.001	0.001	0.073	0.080

6. RECOMMENDATIONS

- Monitoring since 2011 has demonstrated the continued failure of the cliff face at Cowbar Nab, Staithes. It is clear that surveys of the cliff line alone, either from visual inspection, stake measurements or from aerial imagery, would not have captured these changes, which amount to nearly 3,500 m^3 of rock in over 120,000 individual failures.

- We note over the monitoring period that some sections of the cliff face at Cowbar have steepened and in places have generated or exaggerated overhangs, notably in the area directly beneath the section where Cowbar Lane runs parallel to the cliff edge, termed here the 'focus zone'. These overhanging sections are those most likely to fail in a manner that may influence the cliff top in future.

- Observed rockfall indicate how this process may occur. We note that larger failures tend to remove convex cliff sections (overhangs), leaving a near-vertical profile, as was the case in May 2016. It is likely that a similar style of failure will occur at the overhang currently immediately above the rock armour (Profile 2). There is no indication that a failure of a similar nature is imminent, but failure and retreat of the cliff in this location is inevitable. We observe some evidence of smaller rockfalls exagerating this overhang at present. Given the rates and spatial coverage of rockfall that has been observed at Cowbar to date, it is possible that the next large rockfall will change the position of the cliff line. Planning for this eventuality should be considered.

- Any failure of the top of the cliff as a result of the loss of support from the erosion of the cliff face below is likely to be a rapid event. It is, however, likely that this will be preceded by either creep or rockfall from the failing cliff face area, over a period of months to days. Rockfalls from this cliff have however been shown to be rapid to evolve from a point of apparent stability, and so can occur with limited warning. Our effort going forward will be in extracting further information from the high frequency data to provide *a priori* information on changes to the cliff face, and the likely future pattern of erosion.

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Appendix 1: Rockfall in May 2016, data reported to RCBC via email.

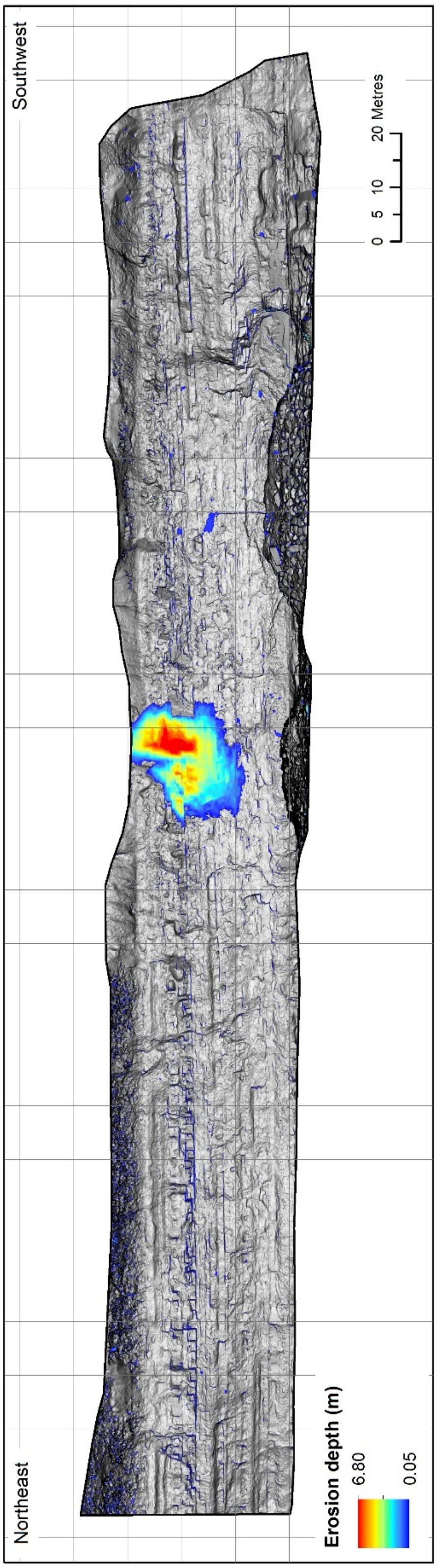

Figure Appendix 1.1: Laser scan derived change model for the May 2016 rockfall, with colours showing the depth of erosion into the cliff face.

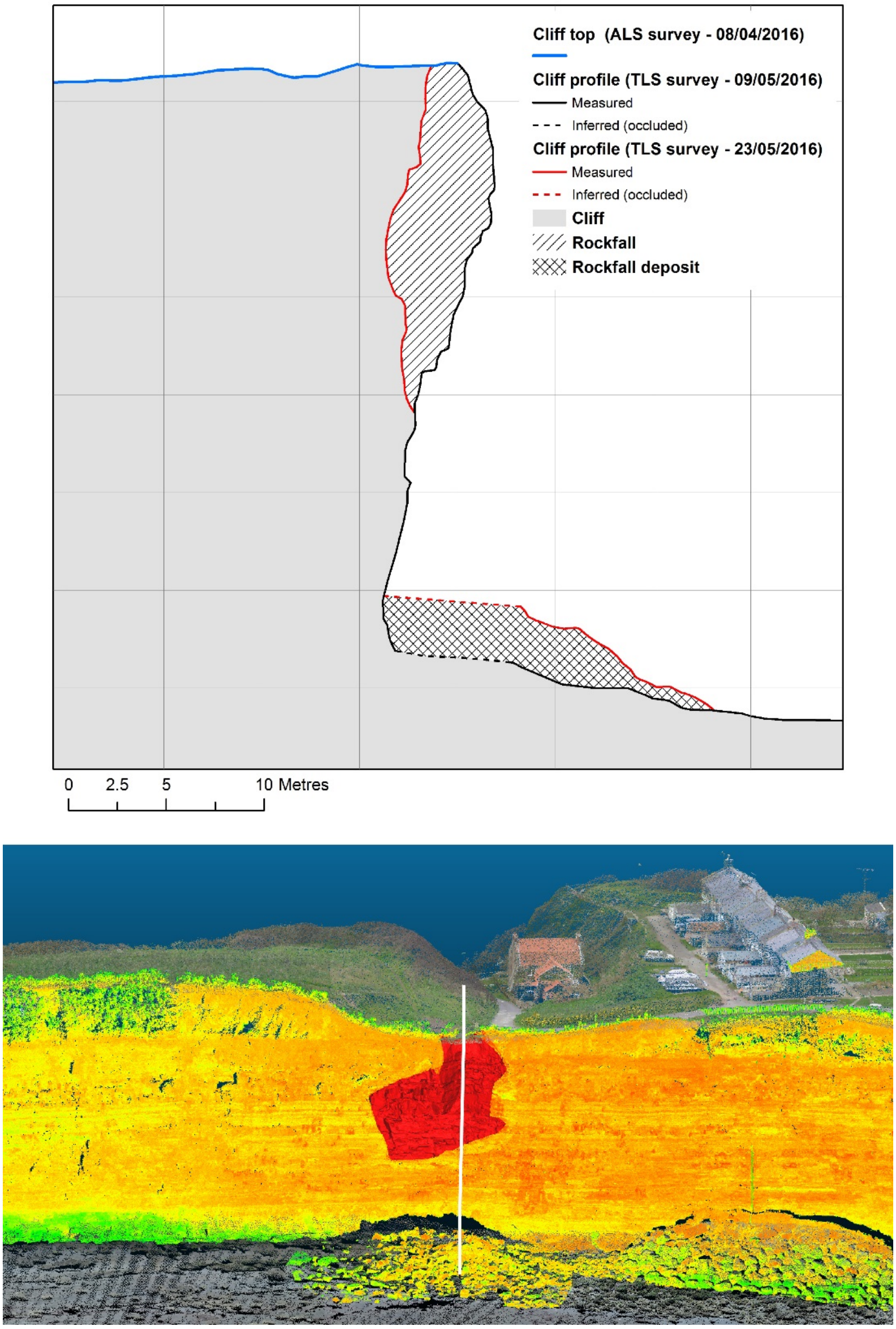

Figure Appendix 1.2 (Top): Cliff profile showing section through the deepest part of the rockfall, the deposit on the foreshore, and the position of the rockfall relative to cliff top. **(Bottom)** 3D render of the rockfall scar.

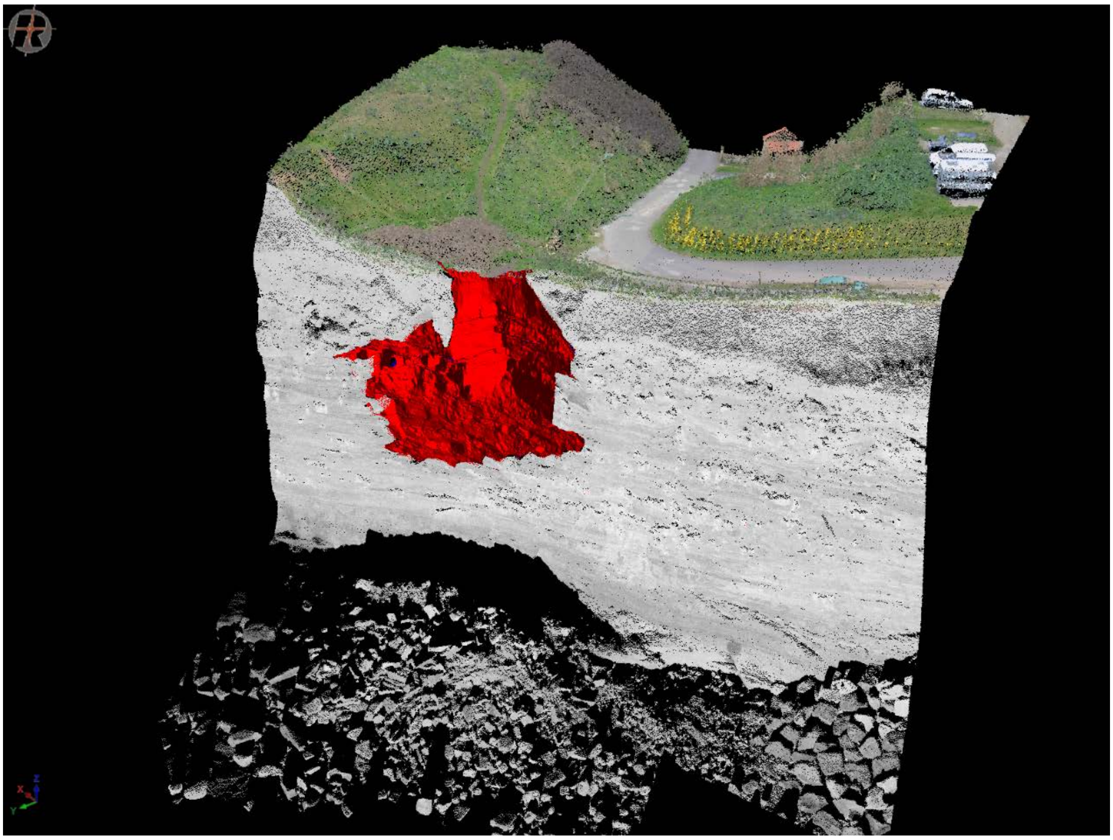

Figure Appendix 1.3: 3D render of the May 2016 rockfall (red), showing the position relative to Cowbar Lane.

DOCUMENT CONTROL SHEET

Project title: Coastal cliff monitoring, Cowbar Nab, Staithes, N. Yorkshire

Revision: 1.2

Status: Final

Date: 17/09/18

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