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# Desk review of coastal evolution studies at UKAEA Dounreay.

Geology and Landscape Northern Britain Programme

Open Report OR/07/017

BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE NORTHERN BRITAIN PROGRAMME

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# Foreword

This report is the published product of a Desk Study Review by the British Geological Survey (BGS) of the coastal evolution studies commissioned by the United Kingdom Atomic Energy Authority (UKAEA), Dounreay between1995 and 2001. It has been undertaken in response to a Proposal Request: Coastal_evolution_BGS.doc, from UKAEA on 24.04.2007. A formal proposal was submitted to UKAEA on 15.05.2007 and a Consultancy Agreement (Contract Number 3100001842) established on 25.05.2007. Written confirmation to commence the review was received on 13.06.2007 and the work commenced on 02.07.2007.

The main staff involved in the review were C A Auton (Geology and Landscape, Northern Britain (GLNB) Programme, BGS Edinburgh), S G Pearson (Coastal Geologist in the Marine, Coastal and Hydrocarbons Programme, BGS Keyworth) and P R N Hobbs (Engineering Geologist in the Physical Hazards programme, BGS Keyworth). The assessment of lichenometry, for dating of evolution of rock surfaces during the last several hundred years, was contributed by T Bradwell and the applicability of cosmogenic dating to determining rock surface ages over longer time scales was contributed by J D Everest (both of the GLNB Programme, BGS Edinburgh). The work was managed and the outputs approved by M Smith (GLNB Programme Manager).

The task was organised and the report compiled by Clive Auton. Stephen Person concentrated on consideration of the robustness of the methods used in the existing studies of erosion rates at Dounreay, from a coastal geomorphological perspective. Peter Hobbs provided an engineering geological assessment of the methods used in the existing studies. All of the authors contributed to identification of possible methods for reducing the uncertainties and to proposals for alternative approaches applicable to the assessment of coastal evolution in the Dounreay Site area.

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# Summary

This desk review evaluates existing studies relating to the evolution of the coast adjacent to the Dounreay nuclear site and assesses their relevance to determining rates of past and future coastal change on the shoreline seaward of the proposed new Low Level Waste Facilities site. It considers the robustness of the existing UKAEA approach, identifies key areas of uncertainty and possible methods for reducing them, and proposes new methods of coastal erosion monitoring that can span the 30 year time frame for low level waste disposal in the new facilities.

The review considered data, results and interpretations of coastal erosion rates for the Dounreay Shaft and Low Level Waste Pits areas, produced between 1995 and 2001. These were presented in five reports and one published paper. The studies used innovative techniques to assess both the erosive processes active on the cliffs and foreshore and to provide numerical estimates and models of annual rates of coastal retreat. These were systematically treated to provide the best evaluations that were possible at the time, but more modern methods are now available that should enable more realistic estimates of erosion rates to be made.

The quality and detail of the data gathered during these studies increased in successive reports. They provide comprehensive literature reviews, summaries of the geology and geomorphology, and forecasts of future coastal erosion rates. Future shoreline and cliff top positions are shown in plan and cross-section. The data is illustrated on annotated aerial photograph mosaics, cross sections and simple coloured plans and maps. Computer-generated cliff-shoreline profiles, graphs of calculated rates of cliff recession, and rockhead contour plots were also produced. However, recommendations for further work were not implemented.

Identification of the principal erosive processes active on the coast were thorough and the conceptual modelling of their effects incisive. The influence of effects of present climate and predominant wave direction were recognised and attempts were made to evaluate the effects of past and future climate and sea-level change. These latter estimates have become somewhat out-dated by the growing and ever changing estimates of future sea-level change and the extent and age of past glaciations. The reports provided estimates of maximum rates postulated from the Shaft and LLWP areas under 3 scenarios. Their possible impact on the new LLWF on time scales of 10,000 to 25,000 years rates is summarised in the report by Morgan and Wilmot as: Scenario – 1 ‘Normal Evolution’~ 2m sea-level rise = erosion concentrated in geos; Scenario 2 - ‘Extended Global Warming’ ~5m sea-level rise = erosion of 55mm pa (550m in 10ka);Scenario 3 - ‘Ice sheet collapse ~ 9.5m sea-level rise = erosion of 55mm pa for first 5ka, 30mm pa for the next 20ka (875m in 25ka). A more conservative rate of 10mm pa was subsequently adopted for the coastal constraint on the location of the new LLWF site.

Many of the key uncertainties identified relate to limitations of the techniques available at the time of the studies. These include positional accuracy of some early measurement positions, the ability to scale-up limited 2 dimensional measurements to site-wide estimates, the difficulties of dating of erosional features and the somewhat simplified understanding of the geological complexity and variation within each site. The geological framework of the Dounreay area is now much better understood, largely due to subsequent and on-going site investigations. The problems of 2D modelling and measurement can now be largely overcome by recent advances in GIS and 3D computer modelling packages and modern field surveying equipment, such as dGPS and Laser scanning. Consequently, a more rigorous approach to monitoring bulk rates of coastal erosion in three dimensional space is possible and, with sequential monitoring over a 30 year period, a more complete four dimensional model of past and future coastal change is possible.

The problem that short-term observations of erosion rates may not be truly indicative of long-term rates, and the possibility that no conclusive change in cliff position occurs during the 30

year operational life of the LLWF still exists. However, the use of lichenometry to date portions of the cliff line and rock platform, offers the opportunity to establish zones where negligible erosion has occurred during the last several hundred years. Sequential (every 5 years) targeted laser scanning of cliffs, slots, notches and foreshore platforms, from characteristic coastal zones (determined by an initial photogrametric survey), allows highly accurate quantitative measurement of both vertical and lateral erosion by a single technique. This, together with programmes of erosion pin monitoring, on-site and laboratory geotechnical testing, targeted to cover the range of rock types known to be present across each scanning site, will give objective geo-referenced measurements. These will enable 3D erosion rate monitoring and also the construction of 4 D bulk rock mass assessment models of coastal evolution that accurately reflect changes during the 30 year monitoring period. The techniques will also produce numerical data suitable for inclusion in time-series computer models of future coastal evolution of the site.

# 1 Introduction

The Dounreay nuclear licensed site is being decommissioned. This is expected to lead to the production of up to 175,000 $m^3$ of solid low-level radioactive waste (LLW), during the next 30 years. Following a Best Practicable Environmental Option (BPEO) study, the UKAEA strategy for the long-term management of Dounreay's LLW is disposal of the waste in new shallow below-surface facilities to be constructed on UKAEA-owned land at Dounreay. A planning application for the proposed new LLW Facilities (LLWF) has been submitted to the Highland Council. To support the development of the Environmental Safety Case for these facilities, UKAEA has employed the British Geological Survey (BGS) to undertake a desk top review of existing studies relating to the evolution of the coast adjacent to the Dounreay nuclear site, to evaluate their relevance to determining rates of past and future coastal change on the shoreline seaward of the newly proposed disposal site.

During the site selection process for the proposed LLW disposal facilities, UKAEA considered that it would be desirable to site the facilities in a location where they are unlikely to be disrupted by the sea in the foreseeable future. This was in order to:

1. Minimise the likelihood of loss of containment of the waste.
2. Minimise potential requirement for future intervention.
3. Minimise any potential dose pathways, as a result of disruption of the facilities.

UKAEA recognised that there is uncertainty associated with future climate change and sea level rise scenarios for the Dounreay site area and that, based on existing data, predicting the future development of the coastline could not be assessed with a high degree of confidence. They also recognised that issues associated with public acceptability of the monitoring regime, to be put in place once the facilities are constructed, need to be taken in into account. UKAEA therefore adopted a simple set of assumptions when considering the potential for coastal erosion of possible sites (as opposed to trying to develop a more elaborate model that may imply greater confidence). The assumptions applied were as follows:

1. For the purposes of site selection there is a need to cater for probable coastal evolution – but not extreme scenarios.
2. It is inherently difficult to extrapolate small-scale process into large-scale, longer term changes.
3. Effects of long-term sea level rise and short-term variations in sea level, e.g. storm surges and waves could be mitigated by locating facilities above 20m AOD.
4. An average rate of coastal erosion of 10mm/p.a was being applied over 10, 000 years.
5. Conservatism was introduced, by assuming full potential extent of erosion is experienced above the 20m AOD level.

### 1.1 STATED REQUIREMENTS FOR REVIEW

This review is undertaken to evaluate UKAEA's current project position on coastal evolution in the Doureay area. It was commissioned primarily as a short desk-based study that covered the following topics:

1. A review of current UKAEA LLWF project position on coastal evolution.
2. Identification of key areas of uncertainty.

3. Consideration of the robustness of the existing approach, given the identified uncertainties.
4. Identification of possible methods for reducing these uncertainties.
5. To produce proposals for alternative approaches to the assessment of coastal evolution and suggest a programme of coastal erosion monitoring to span the projected 30 year time frame for the active phase of Low Level Waste Disposal in the proposed new LLWF.

The review was asked to concentrate on the data and interpretations presented in the following reports and papers:

1 G Morgan (UKAEA) and R Wilmot (Galson Sciences limited), Review of Coastal Inundation Constraint on Location of Proposed Facilities, LLW (06)S2/39, March 2006.

2 J N Hutchinson, D L Millar & N H Trewin, Coast erosion at a nuclear waste shaft, Dounreay, Scotland, Quarterly Journal of Engineering Geology and Hydrogeology, 34 245-268, 2001.

3 J N Hutchinson, D L Millar & N H Trewin, Coast Erosion of the LLW Pits area, Dounreay, Caithness, JNH 149-99/GNGL(99)TR12, June 1999.

4 Galson Sciences, Dounreay New LLW Facilities Monitoring Plan 2007, LLW(07) S2/93, Issue 1, March 2007.

During this work, two other documents were made available:

5 J N Hutchinson, Initial Coast Erosion Study at Dounreay, Caithness, Report JNH 127-95 (Rev. B of GEO2621-21513/02), September 1995.

6 J N Hutchinson & D L Millar, Further Coast Erosion Study of the Shaft area, Dounreay, Caithness. Report JNH 128-95, December 1995.

Of these, a monochrome photocopy of the September 1995 report was made available during the initial desk review and it was fully assessed by the BGS review team and the results reported at the meeting on July 9-10$^{th}$ 2007 July. Colour copies of the September 1995 and the December 1995 reports, and the June 1999 report, were subsequently dispatched to BGS on July 10$^{th}$ (after the initial review had been completed). Consequently, they were only briefly examined and the review comments included here are principally directed at amending initial comments, made prior to July 10$^{th}$, regarding legibility of the original review material, and apparent omissions of data and interpretations that were included in the Journal of Engineering Geology and Hydrogeology paper (Hutchinson et al., 2001).

## 1.2 OUTPUTS AND SCHEDULE OF WORK

A draft of the results and conclusions of the desk review were completed prior to (and for consideration at) a meeting between BGS Staff (C Auton, S Pearson, T Bradwell and J Everest) and UKAEA staff, at Dounreay on 9-10$^{th}$ July 2007. The initial results of the review were presented at the meeting, which was also tasked with identify the logistical and methodological considerations involved in undertaking new monitoring studies of rates of coastal erosion along the shoreline seaward of the proposed new LLWF. In particular, the meeting established the extent of the area of coastline along which the new coastal evolution and monitoring programme should be undertaken, as well as considering new alternative methods of evaluating coastal evolution of the area that were not available to the previous researchers.

The principal new methods considered were:

1. Laser Scanning, for determining short-term (tens of years) change of shoreline profile and position. A 30 year monitoring programme would allow a bulk rock mass assessment calculation of erosion rates within the scanned areas.
2. Lichenometry to determine the relative age of bedrock cliff and shoreline features above the intertidal zone to enable medium-term erosion rate calculations (the last several hundred years) and differentiate zones of relatively active erosion from 'fossil' features which have remained stable. Calibration with measurements of lichens on rock surfaces of known age (gravestones, buildings etc) will allow (by proxy) actual ages of the bedrock features to be established.
3. Cosmogenic Dating which could establish the long-term age (last c. 12, 000 years) of the exposed rock surfaces and thus allow calculation of past coastal erosion rates since deglaciation.

This final report of the desk review incorporates the new outcomes and recommendations identified at the July meeting.

# 2 Overview of the existing studies

The existing work on coastal erosion rates in the Dounreay Shaft and Low Level Waste Pit (LLWP) areas (Figures 1 and 2), which was undertaken in the 1990's, employed a series of innovative techniques to assess both the erosive processes active on the cliffs and foreshore and to provide numerical estimates of annual rates of coastal platform lowering and cliff retreat. A large amount of carefully collected data was produced. The estimates and modelling were systematically treated to provide the best evaluations possible, given the limitations of the technology available at the time, and the cost constraints alluded to in the reports.

During the review of this work several issues became apparent:

a) Only some of the recommendations for further work made in these studies appear to have been implemented.
b) Many other reports of work exist which have a bearing on the results of the erosion studies covered in the 4 reports and 1 peer-reviewed paper initially provided for assessment here.
c) The quality of the initial photocopies provided for review of the Hutchinson (1995) and Hutchinson (1999) reports meant that much of the detail on photographic figures and line drawings with original coloured line work were difficult to assess adequately. This was largely addressed subsequently, by receipt of the coloured copies of the three Hutchinson reports (Hutchinson, September 1995; Hutchinson and Millar, December 1995; Hutchinson, Millar and Trewin, 1999) mentioned above.

The principal interpreted geological and geomorphological results were presented as, annotated aerial photograph mosaics, 2D cross sections and simple coloured plans and maps. These were accompanied by both monochrome and colour photographs of field localities, computer generated graphs of calculated rates of cliff recession, as well as digital and hand-drawn diagrams of geomorphological features, sampling and measurement sites etc. The assessment of these graphic datasets (particularly locations of topographic features mentioned in the text, nature of bedrock exposed on the foreshore, rockhead contour plots and cliff recession models was aided immeasurably by the provision of the coloured copies of the reports.

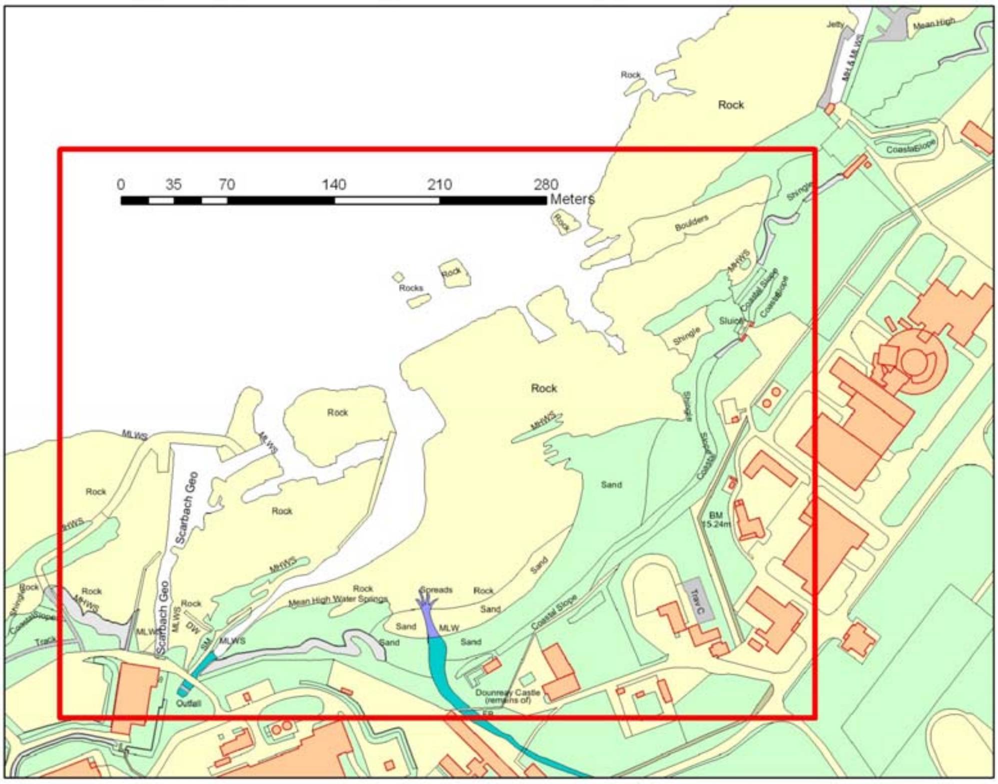


**Figure 1. Extent of the Coastal erosion studies in the Shaft area.**

It is clear that the quality and detail of the data gathered during the erosion studies increased in successive reports. The initial study (Hutchinson, September 1995) compiled with hand drawn maps and diagrams of the shaft area concentrated on establishing the morphology and general geology of the site. It also identified the mechanisms responsible for erosion, gave overviews of erosion rates in Britain, Caithness and at Dounreay and assessed the role of possible future sea-level changes on future erosion rates. The further study (Hutchinson and Millar, December 1995) produced digital plots of accurately located topographic cross sections, sampling points, rockhead contours and computer-generated models of expected cliff positions at specified time intervals into the future. Similar digitally generated data and models were produced for the erosion study of the LLWP area (Hutchinson, Millar and Trewin, June 1999), and the computer-generated models of future erosion profiles and cliff positions were more advanced. However, all of these studies produced essentially two dimensional data (maps and cross-sections) that were converted into modelled cliff line positions for specified dates in the future.

With the recent advent of GIS and 3D computer modelling packages (such as Arc3D Analyst) and modern field surveying equipment, such as GPS (especially dGPS) and Laser scanners, a more rigorous approach to monitoring rates of coastal evolution in true three dimensional space is possible and, with sequential monitoring over a 30 year period, a more complete four dimensional model of past and future coastal change is possible, that will build upon the studies reviewed here.

# 3 Detailed comments on the existing studies

## 3.1 STUDIES OF THE SHAFT AREA (HUTCHINSON, 1995; HUTCHINSON AND MILLAR, 1995; HUTCHINSON, MILLAR AND TREWIN, 2001)

- All of the most significant data and interpretations presented in Hutchinson (1995) and Hutchinson and Millar (1995) for the Shaft area (Figure 1) are included within the Hutchinson, Millar and Trewin (2001) Quarterly Journal of Engineering Geology and Hydrogeology paper, though most of the detailed observations present in the original reports are only summarised.
- The reports provide a comprehensive literature review, a summary of the bedrock and superficial geology, a broad geomorphological survey with detailed maps and accurately located cliff profiles and geological cross-sections, rockhead contour plots, and forecasts of future coastal erosion rates; future shoreline and cliff top positions are shown in plan and cross-section.
- Schmidt Hammer testing and limited petrological analyses indicate that, whilst the bulk of the rock fabric is strong to very strong, the rock mass is prone to erosion by several types of physical, chemical and biological erosive activity. This erosion is most active along discontinuities (faults, joints) and within the most thinly interbedded and weakly cemented, fine-grained portions of cyclic Caithness Flagstone bedrock and within the unlithified superficial deposits that cap the coastal cliffs.
- Erosive processes that were identified include:
  1. Joint/fault/bedding plane preferential erosion
  2. Flagstone recession (slot weathering/sagging)
  3. Corrasion of lower reef dip slopes. This is a *local* process.
  4. Planation
  5. Pyrite swelling
  6. Salt-spray weathering
  7. Wave ‘quarrying’ of blocks. This is a *local* process.
  8. Runnel erosion
  9. Gully (‘sub-geo’) development
  10. Bio-erosion by limpets
- The influence of the present climate and ‘wave climate’ on the strong marine attack regime at the shaft site was recognised, as were the roles of past and future climate states (age and extent of former and future glaciations, eustatic and isostatic sea level changes etc). Evidence for past tsunamis and flooding of the shaft due to storm events was considered, in addition to a predicted net sea level rise.
- The predominant wave climate is from the North and North West and the relatively low cliffs of the shaft area are somewhat protected from the full erosive effect of waves by a series of low (5-7m high) bedrock reefs in the immediate foreshore area.
- The rate of cliff top recession was extrapolated from mapped cliff-line positions on early 19$^{th}$-20$^{th}$ century 1; 2,500 scale Ordnance Survey (OS) mapping and later Dounreay on-site cliff line surveys. Difficulties were encountered in accurately tying-in positions from surveys of different dates.
- The overall rate of cliff recession in the shaft area was seen as a combination of the rate of lateral erosion of the flagstones and that of the overlying superficial deposits.

- Rate of recession of superficial materials (including man-made fill) increases with decreasing rockhead level which changes along the cliff. Variability of recession rate also increases in this case. The cliffs in the shaft area are typically 10-12m high.
- Platform erosion (downward erosion) is the overall factor controlling erosion rate; cliff recession (lateral erosion) follows (Hutchinson, 1986). The ratio between cliff recession and platform erosion (Sunamura, 1983) may vary widely from theoretical in the short and possibly the medium term.
- Extrapolation of cliff recession rates particularly in short and medium term can be misleading (particularly in soft rock or superficial deposits).

## 3.2 STUDY OF THE LOW LEVEL WASTE PITS AREA (HUTCHINSON, MILLAR AND TREWIN, 1999)

- The coastal erosion study of the Low Level Waste Pits (LLWP) area (Figure 2) is more extensive than that undertaken for the Shaft area. The area is characterised by a more complex coastal topography. It is more exposed to the effect of the dominant N and NW waves and, in general, the cliff line is not protected by foreshore bedrock reefs.
- The LLWP area has higher bedrock cliffs (typically 14-15m AOD). Rates of erosion in the superficial deposits appear to be more critical than flagstone (bedrock) erosion rates in determining the expected timing of breaching the pits. Overall erosion rates were also seen to be slightly less critical to pit integrity than the possibility of occasional flooding due solely to forecast sea-level rise.
- As the superficial deposits are generally higher in the cliff than those in the Shaft area, it is the rate of bedrock downcutting and lateral erosion of the flagstones that dominantly governs the overall rate of cliff recession.
- The erosive processes are similar to those active in the Shaft area.
- It was suggested that protective measures against erosion and flooding affecting the superficial deposits capping the cliffs would be effective in delaying the need to abandon the pits, but that these measures would not be particularly effective against the flagstone (bedrock) erosion.
- Joints and bedding planes in the flagstone bedrock provide the pathways for pervasive erosion and ultimately the boundaries of blocks capable of displacement and ‘quarrying’ by wave action. The larger, more persistent, joints provide the boundaries for the major geomorphological features such as reefs, gullies and cliffs.

## 3.3 COMMENTS APPLICABLE TO THE SHAFT AND LLWP AREAS

- Attempts were made to provide quantitative estimates of rates of coastal erosion within the Caithness region as a whole for comparison to rates calculated, measured and extrapolated for the Dounreay site. This was undertaken by, for example, noting the amount of cliff recession landward of bedrock stacks, since the recommencement of marine erosion was assumed to have occurred after deglaciation. A similar assumption was made for the rate of elongation of the geo that penetrates the eastern broch at Green Tullochs, and cliff recession that has damaged Cross Kirk Broch. In the case of the broch sites this assumption is probably valid (although the amount of recession was difficult to determine due to land slipping). It is unclear however, what proportion of the geo growth is truly postglacial as, in some instances, the thickness of the superficial deposits (including glacial tills) infilling the landward ends of geos exceeds that of similar deposits on the adjacent ground. This suggests that the formation of some geos probably commenced prior to the last glaciation and that only an unknown proportion of their

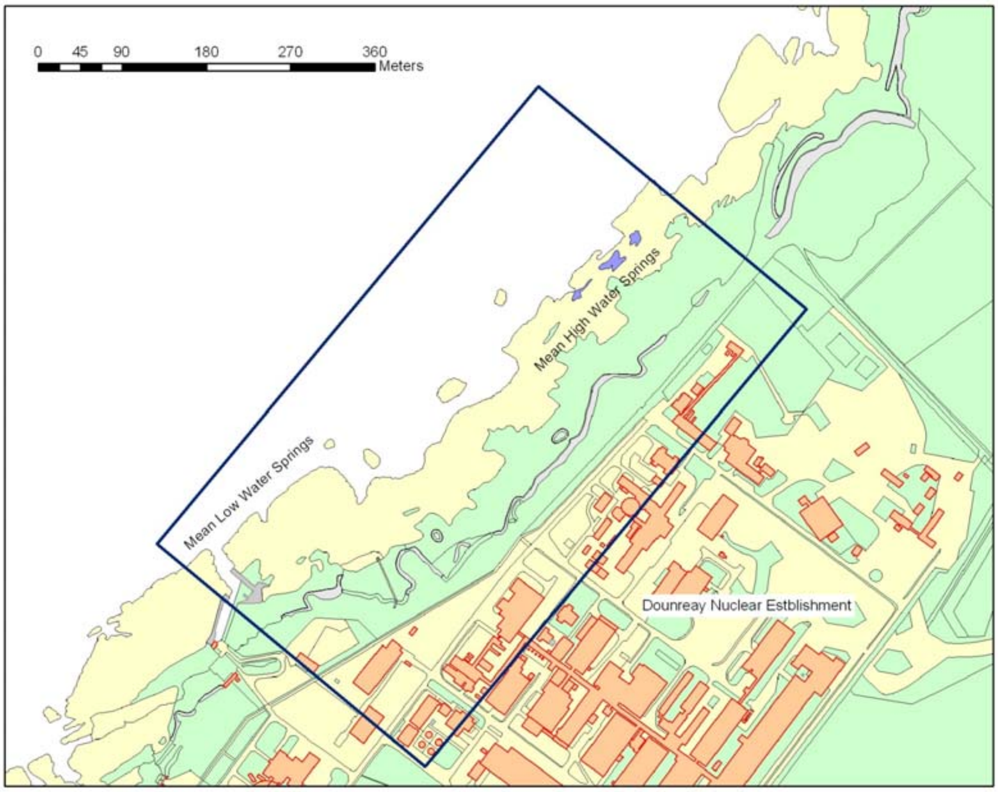


**Figure 2. Extent of coastal evolution studies in the LLWP area.**

recession is due to postglacial erosion. A similar difficulty is encountered with cliff retreat as the exact former position of a cliff top (relative to a broch when it was constructed) is unknown. Even if a broch can be accurately dated, and the amount of penetration or damage can be accurately determined, this will only provide a minimum estimate of the rate of cliff top retreat.

- Petrological studies of 20 samples of resistant and weaker rock units are mentioned in Hutchinson et al. (2001). Apparently these samples were collected along the line of their transect A-A' in the Shaft area. No precise data are given to relate their observations to the rock units within the Caithness Flagstones (Donovan A-C units: Donovan, 1980) and only 4 petrological descriptions for samples from the Shaft area are included in Hutchinson (1995). It is unclear whether these are part of the same sample suite or not. 'Mineralogy' was said to have been established by optical microscopy and XRD analysis, but no detailed petrographical data were provided. Twenty two samples were collected from a logged section of the foreshore of the LLWP area but no detailed lithological or location data were provided. Eleven generalised XRD analyses are presented, related to 'slots', 'tafoni surfaces' and 'flagstones'. As a consequence, the limited petrological and XRD data from both the Shaft and LLWP areas are of little value in describing the relationship between different bedrock types and the rate at which they are being eroded.
- Intersections of joints are key locations where erosion can exploit the resulting local rock mass weakness. The relationship of these intersections to the bedding planes is also a key factor governing zones of active bedrock erosion.
- The weathering profile of bedrock cliffs is highly irregular. Distinct re-entrants ('slots' and overhangs) are formed, but these are less sharply defined than similar slots developed on the bedrock reefs in the tidal zone.

- Localised surface weathering features ('tafoni') are described on the underside of overhangs. These occur within slots in the 'spray zone' and are partly formed due to weathering by salt spray at sandstone/shale bedding boundaries. The size and depth of the largest tafoni were taken to indicate the length of time taken for slot development within the 'spray zone'. The length of a slot divided by its age (as indicated by the size of tafoni), gives an estimate of the relative rate of slot growth.
- Slot recession above the intertidal zone results mainly from chemical weathering and is greatest along slots with ground water seepages; mechanical erosion is considered to be of only minor importance. However, mechanical erosion by wave action is considered to be the dominant cause of slot deepening in the intertidal zone.
- The following mechanisms governing the possibility of marine flooding were recognised (in decreasing probability order):
  1 High tides
  2 Storm waves
  3 Storm surges
  4 Tsunami
- It was also recognised that marine flooding will occur eventually, with or without coastal erosion, due to sea level rise alone.

## 3.4 REPORTS ON THE NEW LOW LEVEL WASTE FACILTIES AREA (MORGAN AND WILMOT, 2006; GALSON SCIENCES LIMITED, 2007)

The Review of Coastal Inundation Constraint on Location of Proposed new LLW Facilities, by Morgan and Wilmot (2006), identified sea level rise and coastal erosion as being the coastal evolution issues of importance that affect the positioning of the new disposal facilities. They recognised that the scale and timing of future climate changes are uncertain and that most climate-related parameters and impacts, except perhaps cliff erosion, are not amenable to verification through monitoring.

This report also presented a brief review of how different rates of coastal erosion might impact on the new facilities over time scales of 10,000 to 25,000 years and under 3 scenarios:

1. 'Normal Evolution'~ 2m sea-level rise = erosion concentrated in geos;
2. 'Extended Global Warming' ~5m sea-level rise = erosion of 55mm pa (550m in 10ka);
3. 'Ice sheet collapse ~ 9.5m sea-level rise = erosion of 55mm pa for first 5ka, 30mm pa for the next 20ka (875m in 25ka).

These rates equate with the maximum rates postulated from the Shaft and LLWP area studies. A more conservative rate of 10mm pa was subsequently adopted for the coastal constraint on the location of the new LLWF site.

The LLWF monitoring plan produced by Galson Sciences Limited provided a limited treatment of coastal change within the 'Climate' section. It dealt with cliff erosion and marine flooding and indicated that erosion of the facilities would not lead to calculated radiation doses greater than those that would be emitted if the facilities remain intact, but the pattern and nature of doses would change.

The monitoring plan also recognises that short-term observations of erosion rates may not be indicative of long-term rates, and that there may be no conclusive change in cliff position observed over the 30 year operational life of the LLWF. Cliff erosion monitoring should therefore be included in the Monitoring Plan, but principally for public assurance only.

### 3.4.1 Particular comments: (Morgan and Wilmot 2006)

- Paragraph 12: There is an assumption that sea level is expected to remain reasonably constant during the next 100 years; this may not be the case. The UK Climate Impacts Programme [UKCIP] 02 (updated December 2005) which provides a regional estimate for net sea-level change in Northern Scotland predicts a 0-10cm rise by the 2080's under a low emissions (optimistic) scenario, and up to 60-70cm under a high emissions (pessimistic) scenario. The recent IPCC07 assessment predicts a eustatic-only global sea level rise of between 9-69cm by 2100 (depending on the future climate scenario adopted). See Section 4 ~ Key Areas of Identified Uncertainty, for further discussion of future sea-level changes.
- Paragraph 16: Quotes Hutchinson et al. (2001) for erosion rates for less resistant lithologies inferred from tafoni growth and for the more resistant lithologies, from erosion pins. Both are questionable and the latter are inadequate as they are based on only 3 pins for a limited section of cliff line.
- Paragraph 23: Recent revisions to climate change scenarios indicate the likelihood for a rising sea level, increased extreme events (storms and storm surges) and a corresponding increase in coastal erosion rates.
- Paragraphs 34/35: The best way to make a more informed judgement on the likely future recession rates, at least in the short term, is to have up-to-date empirical data on current recession rates. Hence there is a need for a coastal monitoring programme.

### 3.4.2 Particular comments (Galson Sciences Ltd, 2007)

- Paragraph 49: Cliff erosion may be observed over a shorter timescale by adopting a "whole area" approach to monitoring, which would detect changes not identified from the measurement of individual profiles.

# 4 Key areas of identified uncertainty and how to reduce them

## 4.1 BEDROCK GEOLOGY

All observations from the reports (1995-1999) and the Hutchinson et al. (2001) paper are related to the classification of the bedrock geology presented on the 1985 edition of 1: 50 000 scale BGS geological map and BGS Regional Guide (Johnstone and Mykura, 1989), with the rocks of both areas being referred to the Latheron Subgroup of the Upper Caithness Flagstone Group (Middle Old Red Sandstone). No use was made of the available new bedrock mapping (at 1: 50 000 and 1: 25 000 scale) that accompanied the Nirex Report on the solid geology of the Dounreay district, (Nirex,1992).This identified numerous previously unmapped bedrock faults across both sites and divided the rocks into new formations with detailed lithological descriptions of each formation. This mapping showed that the rocks in the shaft area were a different formation (with a higher proportion of less resistant flaggy fine-grained lithologies) than those of the LLWP area (with a preponderance of bedded carbonate-cemented sandstones). This means that it may be misleading to apply bedrock erosion rates inferred for the flagstone sequences in the Shaft area to the bedrock sequence in the existing LLWP area, and also to the projected erosion rates for rocks seaward of the new proposed LLWF (see Figure 3).

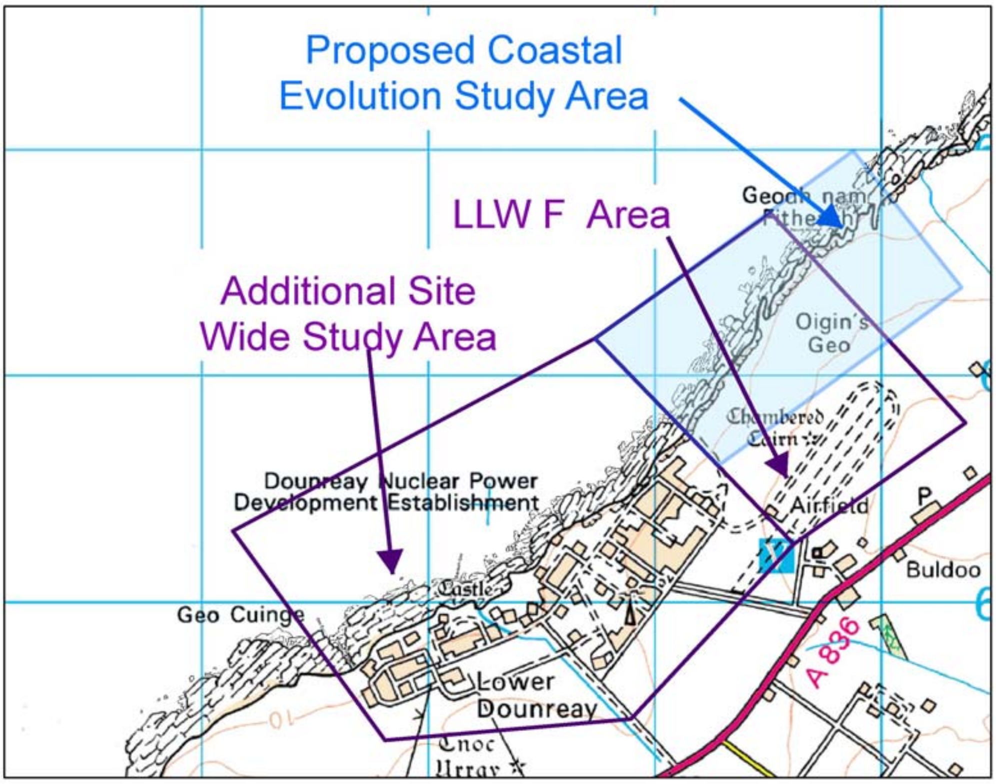


**Figure 3. The location and extent of the proposed coastal evolution study area, the proposed new Low Level Waste Facilities area and the additional Site-Wide Study area.**

The situation is now even less certain. The most recent 1:25 000 scale bedrock mapping (BGS, 2005) attributes the sequence in the vicinity of the Shaft (with the higher proportion of less resistant flaggy fine-grained lithologies) to the Dounreay Shore Formation and the LLWP sequence to the sandstone-dominated Crosskirk Bay Formation. The mapped boundary between the 2 units is highly faulted, but passes landward of the coast that fronts the present LLWP, and seaward of at least some of the ground for the proposed LLWF site. Even more recent site investigations for the LLWF, suggest that the positions of some faults on the 2005 map need to be further modified, and that parts of the LLWF site lie astride the major Geodh nam Fitheach Fault Zone.

What is apparent however, is that long-term estimates of marine erosion rates of the bedrock sequences between the LLWF and the coast need to take account of downcutting and lateral erosion rates for both the Dounreay Shore and Crosskirk Bay formations, in proportion to their outcrop between the LLWF and the coast. They also need to take account of the rates of enhanced erosion along geos, such as Geodh nam Fitheach, which trend south-south-westwards and would, in time, intersect the LLWF site.

Rates and mechanisms of slot recession change above and within the intertidal zone (see section 3.3 above). The intertidal zone slots appear to be eroded more rapidly than those in the cliffs, but the possibility of rising sea levels means that slots that are presently above Mean High Water Springs will eventually fall within the intertidal zone and their erosion rates may increase.

It is unclear whether there has been any attempt to integrate the slot/seepage surveys (e.g. UKAEA, 2005) with calculated rates of recession for individual slots.

Different terminologies (in terms of A-D cyclic units) have been used by Hutchison (1995), Hutchinson et al, (1999; 2001) and Mott MacDonald (Geological mapping and discontinuity data

Appendix A of Hutchinson 1995) which makes it difficult, if not impossible, to reconcile the data sets.

Various types of discontinuities (faults, joints, runnels etc) have been related to different lithologies, but each rock type is described using different terminology by individual authors. It is recommended that all future studies use the accepted terminology for Caithness Flagstone cycles put forward by Donovan (1980).

Although a limited number of Schmidt hammer tests were undertaken, as part of the Shaft coastal erosion study, no attempt was made to link the results to different rock types. This should have been done, in order to relate differences in *in situ* derived Uniaxial Compressive Strength [UCS], (which ranged from 83 ± 36 to 185 ± 82 MPa; Appendix D of Hutchinson and Millar, 1995) to distinguish ‘ strong’ from ‘very strong’ lithologies. The distribution of these different rock types could then have been compared with identified zones of more active and less active erosion. No undisturbed sampling of bedrock for laboratory geotechnical analysis (e.g. slake durability testing) was undertaken. If this had been undertaken at some of the Schmidt hammer sites, it would have enabled further refinement of the *in situ* rock strength data.

There has been no attempt made to survey in detail (c 1: 2,500 scale) the lithological changes in either foreshore area and then to relate the various rock types and the intensity of erosive processes observed (and their products) in an aerial manner. The relationship between rock type and morphology has been made on one cross-section in the Shaft area and on one generalised (un-located) stratigraphical log of the LLWP coastal sequence. This is critical to establishing the pattern of both vertical and lateral erosion. Likewise the intensity/density/orientation/depth of penetration of discontinuities (joints, faults, runnels, bedding planes etc) has been related to generalised lithologies, but the distribution of the different rock types and their associated discontinuities are not generally shown (apart from in schematic cross-sections). Their importance is recognised and stated; their distribution and its significance is not. What is required is outlined below:

### 4.1.1 Improving the resolution and decreasing the uncertainties of new coastal evolution and monitoring studies

Any new coastal erosion study and monitoring programme needs to be based on the following principals:

a) Use a common terminology to describe the rock types.
b) Acquire adequate geospatial information (Grid References, OD levels)
c) Undertake a detailed survey of the aerial extent of A-D units of Donovan (1980) within the survey area(s).
d) Establish how representative the detailed survey areas are of the whole rock mass and its topographic expression (indented coast line with near shore reefs/exposed cliffs fronted by extensive wave-cut platform/geos and stacks etc) along the coastal zone under investigation.
e) Record type, density, orientation and penetration of discontinuities (faults, joints etc) within each mapped rock/landform unit (and any differences <u>within</u> segments of each unit).
f) Relate mapped lithologies/segments to petrological/geotechnical sampling (Schmidt hammer/slake durability testing)/laser scans, photographic images etc. This adequately characterises each lithological unit, or portion of the foreshore and cliff, in terms of its strength.
g) Then relate measurements of erosion rates derived from erosion pins/laser scans and records of the types of erosion identified and their products (e.g. slot deepening, block ‘quarrying’). This identifies which lithologies, and which parts of the coast, are being subjected to which types of erosion. When these results are combined with baseline data from time-series analysis of cliff-top positions

obtained from georectified images of existing vertical aerial photography (available for flights from the last c, 30 years) and large-scale (1: 2, 500) historical OS maps (available from the 19th century onwards), a clearer assessment of rates of present coastal evolution, past coastal erosion (over the last c. 150 years) and future rates of erosion can be made.

This requires use of GPS (often dGPS) and that the data be collated within a GIS and integrated within a 3D modelling package. This would allow recognition of portions of the cliff/foreshore with varying degrees of resistance to erosion (zones of weakness, hard resistant fossil cliffs etc. This can then be checked by laser-scan surveys of cliffs and platforms above the intertidal zone and dated by lichenometry (see below).

We suggest that the approach outlined above be adopted for the base-line survey associated with the proposed 30 year coastal monitoring for the LLWF area.

This will allow the true rate and variability of coastal recession in the area to be determined more precisely, allow more realistic monitoring of present erosion and also modelling future coastal retreat. At present, this has been done by applying a uniform value of lateral retreat of c. 10mm pa to a stretch of coast, as a whole, and then extrapolating it (taking into account expected changes of relative sea level) into an overall rate of retreat for the next 100 000 years. The rate will change significantly within short distances, dependant on geological and topographic differences along the coast and, in particular, the relationship between the density and orientation of zones of weakness relative to the prevalent wave direction.

## 4.2 SUPERFICIAL GEOLOGY

A somewhat similar degree of uncertainty is apparent when considering what is now known about the thickness, nature, variability and age of the Superficial deposits in the Shaft area in relation to the assumptions made by Hutchinson (1995) and Hutchinson et al. (2001).

In the studies under review, the generalisation was made that the Quaternary sequence solely comprised glacial till, of possible Wolstonian age (c.186-128, 000 years), or of Late Devensian age (c. 26-13 000 years), or a mixture of both, resting on bedrock. The till was known to be capped by a variable thickness of artificial fill resulting from several phases of construction of the Dounreay site; the nature of the ‘fill’ was known to be variable. There was little further consideration of the unconsolidated materials, apart from information on the thickness of fill capping the existing LLW pits. It was inferred that the fill would be less resistant to erosion than the till, if the site were breached by the sea. However, rockhead data, provided by the AEA, was taken into consideration for the LLWP study.

Subsequent geological mapping, drilling, pitting and trenching, at site investigations across the Dounreay Site, have provided much greater detail on the rock head depth and the nature of the sequence. Investigations for the LLWF have confirmed a generally thin (<2m) discontinuous mantle of till overlying cyclic bedrock sequences on the proposed site. Down-dip, the rock head surface has a ‘saw-toothed’ appearance, with preferential weathering of A and B Donovan units whilst more resistant D unit sandstones stand perhaps c. 1m higher. The upper ground surface is more regular, with thicker till deposits in the linear bedrock hollows formed by the weathered intervals. The till is generally capped by thin peat or peaty soil. This situation appears typical of most of the ground between the LLWF and the coast (though this is the subject of current field investigations, principally by trial pitting and ground geophysical surveys).

The Superficial sequence in the vicinity of the shaft is much more complex, with variable thicknesses of Postglacial blown sand, lake clays, peats, sands and silts overlying alluvial and glaciofluvial sands and gravels. All of these weakly consolidated sediments rest on a variable thickness of till of at least 2 and possibly 3 types. This complex sequence is capped by a variable thickness of sandy, cobbly and/or clayey fill; the whole sequence may exceed 9m in thickness locally.

Several consequences follow from these general observations:

1. The nature and variability of the superficial deposits and fill need to be taken into account when modern erosion rates are extrapolated to coastal sequences seaward of the LLWF. This is particularly true of erosion rates for the superficial deposits in the vicinity of the shaft (where much less resistant material as well as till is present).
2. Rockhead depth is of critical concern.
3. Geotechnical data from existing and ongoing site investigations could be used to characterise more fully the relative resistance to erosion of different types of superficial deposits and fill. This would help validate extrapolated rates of both vertical and lateral erosion.
4. Recent investigations now strongly indicate a Late Devensian age (13-26ka) for the youngest glacial deposits in the Dounreay area. This constrains the onset of most sea-level erosion to be later than that deglaciation (locally thought to be c. 14.5-15.5ka), though parts of central Caithness are known to have been ice-free by c. 13.5ka. These recent investigations also suggest that short-lived high relative sea levels of perhaps c. 20-25m AOD may have been present locally in the Dounreay area c. 14-15ka BP. What is also clear, is that relative sea levels of c 2m AOD (but < 6m AOD) were present locally c. 6, 000 years ago, but the inference, by Hutchinson (1995), that all marine erosion of the current coastline has occurred during the last 6, 000 years is erroneous.
5. The presence of abnormally thick sequences of Quaternary deposits at the heads of some geos suggests that the latter may be in part fossil features and that they may have been initiated pre-glacially. The composite infill of some major clefts (e.g. Wester Clett) may span several glacial cycles. This argues for differential erosion along much of the rocky cliff line and that many of the bedrock cliffs may have suffered only very minor retreat over thousands of years.

### 4.2.1 Reducing the uncertainties related to the nature of the superficial deposits in new coastal evolution and monitoring studies

Apart from obtaining further detailed data on rockhead depth from boreholes, trenches, trial pits and geophysical surveys from on-going site investigation studies, new geotechnical data (particle size analysis, liquid and plastic limits, compaction and hydraulic conductivity tests) could be collected from ongoing site investigations and be combined to more fully characterise the relative resistance to erosion of different types of superficial deposits and/or fill encountered between the LLWF and the coast.

Additional data on the strength and density of the superficial deposits might be obtained by ultra-lightweight PANDA penetrometer traverses between the cliffline and the site. The technique is quick and the results easy to interpret, but although the PANDA has been successfully used in till deposits at other localities, the proportion of large clasts within the fabric of the till in Caithness mean that it might prove unsuitable at this locality.

## 4.3 FUTURE RELATIVE SEA-LEVEL RISE

A predicted rate of future sea-level rise of c. 5 mm/pa to 2100, then 10 mm/pa to 2500 was used by Hutchinson (1995), Hutchinson and Millar (1995) and Hutchinson et al. (1999, 2001). These kinds of estimates are continually changing as knowledge increases.

Latest estimates can be regularly assessed by monitoring the UKCIP Web site: UKCIP02/IPCC07 or UKCIP08 accessed using the following URL:

http://www.ukcip.org.uk/scenarios/ukcip02/documentation/ukcip02_scientific_report.asp

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|---|---|
| Chapter 6: Future Changes in Sea Level and UK Marine Climate Pages 72-80 | 782 KB |

Monitoring of data from this Web site (or any future successor) should be undertaken regularly throughout the 30 year active cycle of the LLWF, so that updating of site monitoring and remediation procedures can undertaken in a timely manner, if a significant change in the rate of sea-level change is recognised or predicted.

## 4.4 ACTIVE EROSION

Active monitoring of lateral cliff erosion has been confined to three steel pins installed within a 20 m stretch of the cliff toe, to the NW of the shaft enclosure and immediately to the north of the retaining wall. These pins have proved rather unsatisfactory as they are of mild steel and the possibility of metal corrosion has interfered with the measurements of rock erosion measured against them. They are no longer available for measurement. It is proposed that any new monitoring programme be accompanied by an extensive network of stainless steel erosion pins and that pin measurements be taken on an annual basis (see Section 5; new alternative methods, for further details.

The best assessment of downward erosion of rock platforms relied on measurements of the lowering of bedrock profiles around outfall pipe installations of known age in the LLWP study area. This, at best, is probably fairly inaccurate and has several uncertainties associated with it:

1. How representative are the profiles (and hence the erosion rates) along the outfall pipes of the overall morphology and geology of the LLWP study area?
2. Have additional measurements been made of the profiles since the initial measurements reported by Hutchinson Millar and Trewin in 1999?
3. Are all of the outfall pipe measurement sites still available, if routine (e.g. 5 yearly) measurements of the profiles is recommenced?

If a new site-wide (Figure 3) coastal evolution study is eventually undertaken, then these outfall pipe installations should be revisited and re-measured by dGPS and laser scanning.

## 4.5 ACCURACY OF CLIFF TOP POSITIONS AND MEASUREMENT OF CLIFF TOP RECESSION

### 4.5.1 Aerial photography and large-scale maps

The problems associated with accurately delimiting the historic positions of the top of the cliff line from historical OS maps have been documented in the reports being reviewed. This inaccuracy can be partially overcome by georectifying the datasets within a GIS, but the inaccuracies of the initial surveys still remain. Nevertheless, a more accurate assessment of changes in the historic positions of the cliff top over the last c. 150 years, using the tools available in Arc3D Analyst, are now possible. These should be undertaken as part of the baseline of any new erosion study. Similar techniques can be employed on orthorectified aerial photographs and SocetSet software can be used to digitize cliff top positions and the location of other significant topographic features identified on high resolution digital images of aerial photographs.

The availability of suites of time-series air photographs and large-scale historic OS maps for the site area and the costs of establishing copyright/licensing agreements involved with scanning and digitizing this material would need to be established, prior to this work being undertaken.

### 4.5.2 Lichenometry

Lichenometry provides a potential method for establishing the relative age of cliff faces and rock surfaces above the intertidal zone which spans the last several hundred years. The method is described in detail in Section 5 below.

### 4.5.3 Cosmogenic dating

Measurement of accumulation of cosmogenic isotopes in quartz provides the possibility of dating stable rock surfaces over the last 10, 000 years or more, possibly since the deglaciation of the coastline (c. 14.5 ka BP). Isotope accumulation will have continued on rock surfaces that have been exposed at the ground surface since the last deglaciation. The isotopes have the potential to date deglaciation quite closely and hence provide a 'start date' for postglacial coastal erosion in the area. Sandstones within Caithness Flagstones are commonly sufficiently quartzose for isotopes to accumulate, but rates of downward erosion of 5mm pa (as suggested by Hutchinson) would remove much of the material in which the isotope signal is preserved faster than the signal can accumulate. This method, if applicable, would be principally useful for identifying long-lived bedrock features (possible fossil cliffs) and relative accumulation figures might also confirm areas of the foreshore where erosion is much less than 5mm pa. However, the field reconnaissance visit of July 10th showed that the rocks exposed along the coast in the Dounreay area are far from ideal for cosmogenic dating. The quartzose rocks are generally fine- to medium-grained sandstones, whereas coarse-grained sandstones or preferably quartzose crystalline rock types are required for successful laboratory analysis. Resistant quartz veins within the flagstones could provide suitable alternative material, but no such veins were seen in the cliffs and foreshore during the July site visit.

### 4.5.4 Differential GPS traverses

Rates of cliff top retreat during the 30 year monitoring programme can be established by dGPS traverses along the cliff top. These can be undertaken in conjunction with laser-scanning and will act as a baseline for these surveys.

# 5 Proposed new methods of erosion assessment and monitoring for the LLWF area

The review presented above indicates that a more comprehensive assessment of coastal evolution and monitoring of erosion rates is possible than that previously undertaken. New techniques that were not available during the 1990's, including laser scanning and Arc-based 3D modelling, have the potential to acquire and integrate large digital datasets and derive quantitative measurements of coastal change.

The programme of monitoring and assessment proposed below is suggested for the shoreline seaward of the LLWF site. A similar body of work could be undertaken for the remainder of the Dounreay site area, but further field reconnaissance would be necessary to fully establish the scope of work for this ground (the 'Additional Site-Wide Study Area' of Figure 3).

A terrestrial laser scan monitoring programme is proposed. Ideally a “whole area” approach could be attempted rather than measuring individual profiles, in order to give a broader appreciation of coastal recession, and allow volume change calculations to be made. Vertical platform erosion and lateral cliff recession measurements can be completed in one operation, rather than using separate methodologies.

## 5.1 PROPOSED EROSION MONITORING BY LASER SCANNING

The BGS Riegl LPM Laser scanning system (Figures 4 and 5) is state-of-the-art and is ideally suited to monitoring erosion and modelling geological features. It does not rely on fixed points due to the fact that it is oriented using Leica differential global positioning (dGPS). However, it can also be used to tie-in to fixed points should they be available. This method allows multiple scans to be made from diverse locations, both on the platform and cliff-top. These are then oriented and combined to produce a single 3D model. This can be rendered in the form of either a transparent point-cloud, coloured from ortho-rectified digital images from the built-in camera, or a solid triangulated surface with the imagery draped on it. The BGS methodology allows accurate and detailed measurements to be made from these models. Sections can be generated and volumes, areas and displacements measured. In addition, the BGS’s new 5 sec Leica TPS 1200 total station includes an IR rangefinder and has integrated Smart GPS. This means that the laser scanner, dGPS and total station are acting in concert to provide a combination of high accuracy measurements for individual survey points and high density, medium accuracy point data of natural features. This capability is particularly important along the Dounreay coast because, whilst it is important to accurately measure changes at specific locations, it is not sufficient. Changes *throughout the area* should be measured, particularly as they may occur in unexpected locations.

The topography of the coast seaward of the LLWF site is complex, and for the success of the ‘laser-scan/dGPS/total station’ method a carefully planned survey is required. The laser scan principle requires line-of-sight on the subject, as any obstructions produce shadows or holes in the model. This is remedied by overlapping multiple scans taken from different vantage points. For example, the ‘sawtooth’ reefs characteristic of some parts of the shore platform would necessitate detailed planning of scan position layout in order to minimise ‘shadow’ areas. Similarly, the bedding plane ‘slots’ and overhangs would require low elevation vantage points on the platform in order to provide close range detail. In effect, the reefs would be treated as ‘mini-cliffs’ and the scanner locations would generally be at the reef-tops and the reef-bases (Figure 6).

The laser-scans would be tied-in to a series of baselines which would run parallel to the cliff and reefs, at each end of which would be installed a new permanent stainless steel pin fixed into a rock-drilled hole using marine engineering mortar.

### 5.1.1 A proposed refined laser scanning methodology

The field reconnaissance visit of July 10th led to a refinement of the suggested ‘whole area’ approach, originally put forward at the discussion with UKAEA staff on the previous day. Several factors became apparent during the field visit:

1. The extent of the coastal zone under consideration for the LLWF (between the eastern fenced limit of the Dounreay Site and Geodh nam Fitheach; some c. 1.4 km of coastline) is large. It is comparable to that of the Shaft and LLWP areas combined (see Figures 1, 2 and 3).


**Figure 4. Riegl LPMi800HA Long-range scanner.**

(scan rate: 1000 points per second; Range: 800 m; Range accuracy: +/- 15 mm)

**Figure 5. Laser scanning a coastal cliff.**

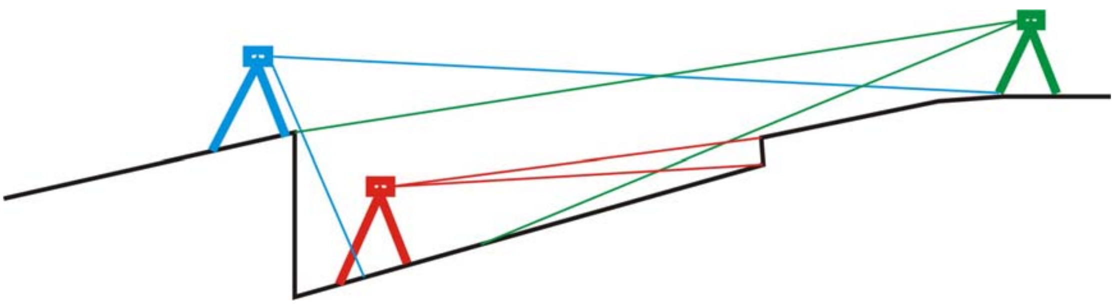

**Figure 6. General arrangement of scanner locations in relation to cliffs and reefs.**

(Blue and green scans cover reef scarps & dip slopes, while red scan covers detail in ‘slots’)

2 Much of the coastline is highly indented, steeply cliffed and has a very narrow 'platform area'. Much of it is inaccessible, even at low tide. This means that many more scans would be needed to characterise the whole area than would be the case with a more linear cliff line and wide foreshore.

3 The inaccessibility of many parts of the zone and the limited 'scanning window' at lowest tide means that only selected portions of the coastline can be scanned safely.

All of these factors, as well as the possibility of inclement weather (storms, fog etc) would mean that attempting to scan the 'whole area' would be prohibitively expensive and time consuming.

A tiered approach is now advocated, in which six representative coastal zones are identified that will characterise the whole area. These would be scanned to produce 3D models and detailed scans made of selected features (slots, cliff notches arches, discontinuities, erosion pits etc).

Six representative sites are envisaged:

- 2 examples of indented cliffed coastline
- 2 examples of exposed cliffline with wide platform and basal cliff notches
- 2 Geos, one of which would be Geodh nam Fitheach

Erosion pin, Schmidt hammer testing and geotechnical sampling sites would be undertaken at known locations recorded on the scans and by dGPS during this initial survey. The proportion of the whole area represented by each laser-scanned area would be established by photogrammetric analysis of the whole stretch of coast prior to the commencement of the first scanning survey and the exact extent of each scanning area and number of scans adjusted to produce the most representative results possible. This will allow scaling-up of the bulk volume change measurements calculated during successive surveys to give figures for the whole area of interest.

The monitoring programme would include re-scanning the same area at 5 yearly intervals, tying in to the pins installed as part of the initial survey (see section 5.2 below). Comparison of the first and second models would then be made, in a software package such as QT Modeller, revealing (and scaling) graphically the zones where changes have taken place. The same scanner locations do not have to be re-occupied in the second, and subsequent surveys, as in the first. However, it would be beneficial to do so. Cliff-top dGPS traverses and erosion pin measurements can be taken at the same 5 year interval (the latter could be undertaken more frequently by UKAEA staff if necessary).

The scanner produces a 'point cloud' of millions of correctly georeferenced individual readings that are amenable to inclusion in a variety of 3D modelling packages and the readings would be compatible with data collected in successive iterations of monitoring over the 30 year proposed time-frame. Indeed, scanning equipment and processing techniques are likely to evolve over time, so that resolution and speed of survey is likely to increase as time passes.

Using the methodology described above a monitoring programme could be instituted which would pick up changes in the large-scale features such as the cliff and reefs and also in the minor features such as the 'slots', overhangs and transported blocks. The scale of the changes detectable with this system is difficult to quantify accurately, due to errors emanating from a variety of sources including the laser range-finding, the angular registration of the laser in both vertical and horizontal planes, and the positioning of the baselines using the dGPS and/or total station. However, it should be possible to resolve changes in *xyz* position of around 5 cm and greater in any direction using this system. This will partly depend on the range of the subject, its position in relation to each scan and the density of the point cloud at that position. Thus any movements or changes of this magnitude within the survey area would be detected without precognition of their locations (as would be the case if relying solely on a pin survey**).**

In addition to the above, recently available software (Split-FX from Split Engineering, USA) enables stereographic plots of structural discontinuity features to be produced automatically from laser scans. This software could be used to provide a comprehensive and accurate model of the rock discontinuities across the scanning sites with minimal field work.

## 5.2 EROSION PIN MONITORING

An extensive network of numbered erosion pins, (c. 40-50) located by dGPS survey should be inserted both vertically into the foreshore rock platform and laterally within the scanned portions of monitoring area. The pins will be distributed to include all of the principal rock units (covering the whole range of typical lithologies and the full spectrum of resistant and less resistant rock types encountered). The positions of pins in faces relative to both the predominant and subsidiary wave directions will be established to assess the relative influence of aspect. Some pins will also be installed as markers of laser scan positions (to enable accurate measurement of changes in vertical elevation at mm accuracy). This will build upon and update the technology employed by Hutchinson. Installation of the pins would take place as part of the baseline survey.

By employing a population of pins, measurements can be continuous over the 30 year monitoring time, even if some pins are removed by erosion of weak layers and new replacement pins could be added to rebuild the data set. If, for example, pins are found within loose blocks quarried by wave action, but displaced across the shoreline platform, the pin will enable ready identification of each bock and allow measurement of its displacement.

## 5.3 SCHMIDT HAMMER TESTING

This is a rapid comparative test for determining the ‘rebound hardness’ of strong rocks. This provides a measure of the strength and competence of the rock. Correlations with the Uniaxial Compressive Strength (UCS) test are available. This test is not a British Standard, but is an International Society of Rock Mechanics (ISRM) recommended method. The Schmidt hammer test would be used in the field on the principal lithologies identified in each representative scanning site and the results linked to erosion pin and geotechnical sample localities in the manner outlined in Section 4.1.1.

## 5.4 GEOTECHNICAL LABORATORY TESTING

A key test in the assessment of rock erosion and the significance of bedrock durability in long term erosion model predictions is the slake durability test. This is not a British Standard, but is an International Society of Rock Mechanics (ISRM) recommended method. The test provides a controlled form of mechanical and liquid degradation of a rock sample. The relevant aggressive liquid, in this case sea water, can be used rather than the more usual tap water. Samples would again be taken of the principal lithologies identified in each representative scanning site and the results linked to erosion pin and Schmidt hammer measurements.

## 5.5 ESTABLISHING A MEDIUM-TERM BASELINE OF BEDROCK COASTAL RETREAT BY LICHENOMETRIC DATING

Until recently, there appeared little prospect of objectively measuring the rate of coastal erosion at the Doureay site over more than the last few decades, apart from comparing cliff top positions from successive early Ordnance Survey maps, and by inferences made from isolated measurements of the impact of coastal erosion on dated archaeological sites such as brochs.

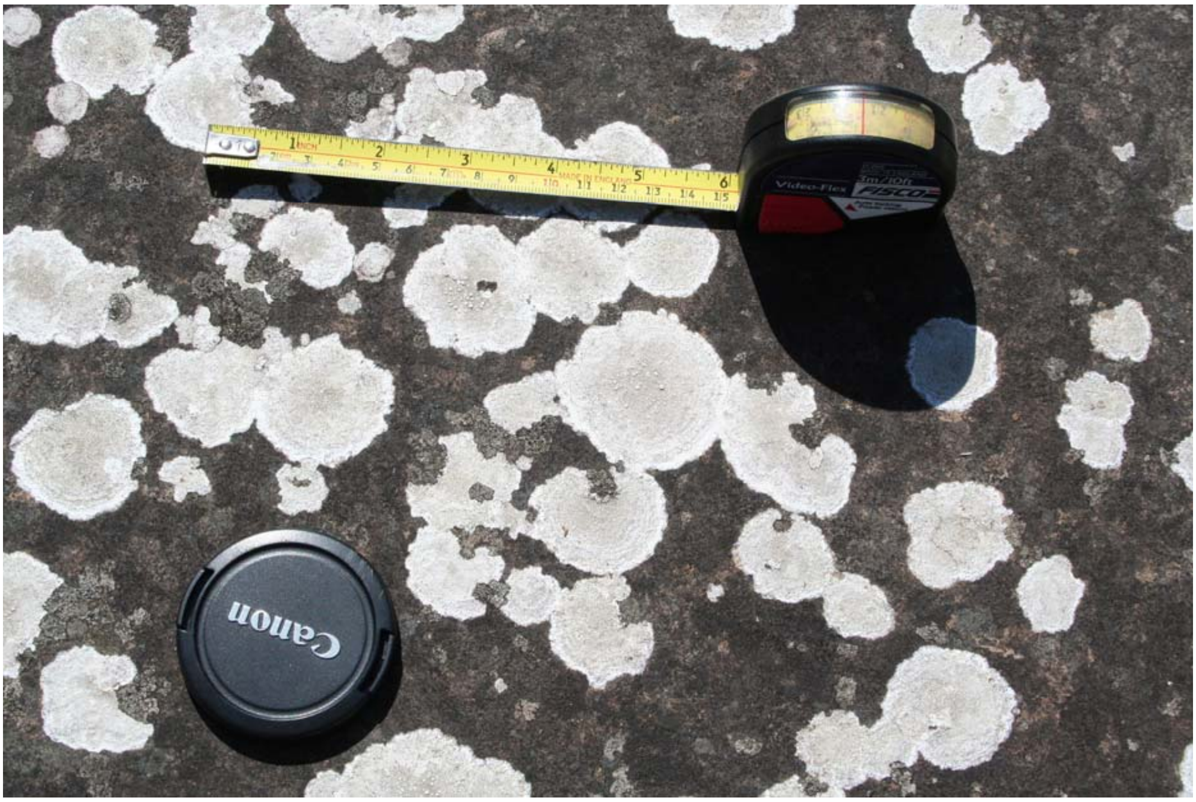


**Figure 7. Lichen-covered flagstone surface from the proposed LLWF coastal monitoring area.**

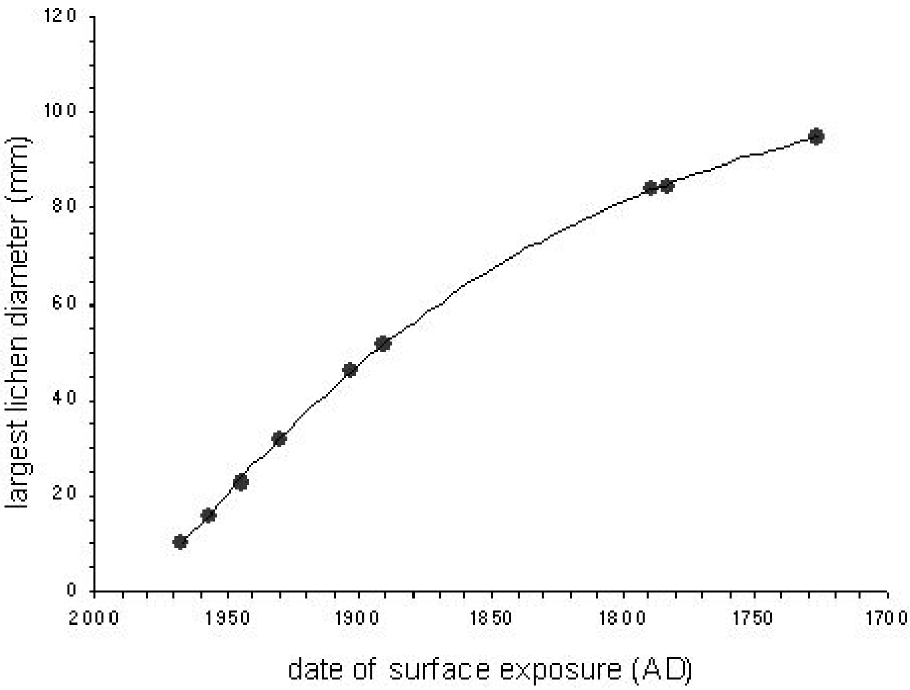


**Figure 8. A typical lichen growth calibration curve.**

Lichenometric dating uses measurements of lichen size or other indices of lichen growth to determine the age of a rock surface when other dating techniques are inapplicable. The technique proves most successful on high-latitude and high-altitude rock surfaces formed within the last few centuries. Traditional lichenometric procedures use the size of the single largest lichen as an indicator of surface age, but most modern workers use the mean of a small number of 'largest lichens' as a more reliable indicator of surface age. Empirical rates of growth for certain lichen types are established and these growth rates can be locally calibrated by measurements of lichen size on rock faces of known age (dated grave stones in nearby church yards are prime candidates).

At present, this method offers the best option for providing objective data on the ages of rock surfaces along the coast spanning the last several hundred years until the present day. Rock surfaces on both the cliffs and parts of the foreshore in the LLWP area are recorded as being 'lichen covered' by Hutchinson et al. (1999) and lichen covered flagstone surfaces are known from BGS mapping to be widespread along the cliffs of the area (Figure 7). These observations were confirmed during the site field reconnaissance visit of July 10th 2007. Coastal grave yards exist at St Mary's Kirk (Crosskirk) Brims Ness and at Reay church. Good lichen-covered dated grave stones were seen to be present at Crosskirk and Brims Ness, which were visited on July 9th. These dated rock surfaces will enable a calibration growth curve to be established. Relative ages of rock surfaces on the coast can be established and calibration may enable approximate calendar ages to be calculated. Other possible calibration sites include the 16th century Dounreay Castle composed of flagstones found within Dounreay site, whilst more recent calibration (last 40-50 years) is offered by more modern stone structures of known age within the site area.

All of the above observations indicate that dating of the cliffs and parts of the platform within the LLWF monitoring area are possible by lichenometry. This is essentially a single baseline measurement study that will be relatively quick and easy to undertake. It will allow a refinement of the calculated overall rates of cliff retreat and also establish relative rates for parts of the coastline that have been retreating more or less rapidly than others over the past few hundred years.

# Additional References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

DONOVAN, R.N. 1980. Lacustrine cycles, fish ecology and stratigraphic zonation in the Middle Devonian of Caithness. *Scottish Journal of Geology*, **16**, 35-50.

BRITISH GEOLOGICAL SURVEY. 2005. Dounreay, Scotland, parts of sheets NC96, ND06 and ND 07. Bedrock. 1:25 000 Series. (Keyworth, Nottingham: British Geological Survey.)

HUTCHINSON, J.N. 1986. Cliffs and shores in cohesive materials: geotechnical and engineering geological aspects. *Proceedings: Symposium on Cohesive Shores, Ontario.* National Research Council of Canada, Ottawa (Publication. NRCC26134), 1-44.

JOHNSTONE, G S, and MYKURA, W. 1989. *British Regional Geology: the Northern Highlands of Scotland* (4th edition).(London: HMSO for the British Geological Survey.)

NIREX. 1992. *Solid geology of the Dounreay District.* UK Nirex Ltd Report. **655**.

SUNAMURA, T. 1983. Processes of sea cliff and platform erosion. 233-265, in *Handbook of Coastal Processes and Erosion*. (P. D. Komar, editor). (CRC Press Inc. Boca Raton, Florida.)

UKAEA 2005. Foreshore seepage survey, Summer 2005. UKAEA Report EPD(05)P222.