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New Low Level Waste Facilities

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Quantification of coastal erosion at Dounreay using historical photo-grammetry and remote sensing data

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SUMMARY:

This document presents the findings of studies, undertaken between 2008 and 2010, by the British Geological Survey, of the evolution of the coastline in the Dounreay area using georectified historical topographic surveys, aerial photographic data and supporting walk over surveys.

The datasets generated during the study have been complied within an Arc9.2 GIS that should be viewed in conjunction with this report.

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CONTENTS

1. ACKNOWLEDGEMENTS....................3

2 EXECUTIVE SUMMARY....................4

3 INTRODUCTION....................7

4. GIS CREATION (REMOTE SENSING AND DIGITAL DATA INTEGRATION)10

Aims....................10
Map and aerial photography datasets....................11

5 DIGITISATION OF OS MAP DATA

General evaluation of the 1: 2,500 scale topographic bases....................13
Results....................17
Interpretation of the results – NLLWF-AOI and DS-AOI....................18
Cliff Top/Cliff Edge Positions.................... 18
Low Water Mark Position.................... 21
High Water Mark Position.................... 21

6 ADDITIONAL TOPOGRAPHIC DATASETS SUPPLIED BY DSRL DURING THE PHASE 1 STUDY

Evaluation of the Dounreay 1955 Site Survey....................23
Cliffline_Shapefile....................23
Interpreted_base_of-superficial_deposits....................25
Gullies.shp....................25
Coastal Erosion Markers....................26
The Differential GPS Survey June 2008....................28
Field data.................... 28
Limitations of the dGPS survey.................... 29
Comparison between dGPS and Arc digitized cliff top positions from the OS maps....................30
1872/1906 surveys.................... 30
1966/67 surveys.................... 31

7 **WALK-OVER RECONNAISSANCE OF THE DS-AOI FORESHORE....................32**

Hyperlinking photographs and Locality Points in the GIS Project....................32
Viewing hyperlinked photographs in the GIS....................33
Results of the Walk-over Reconnaissance....................33

8 **PRODUCTION OF GEORECTIFIED STEREOSCOPIC AERIAL PHOTOGRAPHIC IMAGES....................39**

Phase 1 study photogrammetry....................39
Phase 2 study photogrammetry....................40
Limitations on interpretation and digitisation of the aerial photography datasets.......42
SocetSet Interpretations....................45
Results....................46
2004 digital aerial photography.................... 50
2004 cliff top position.................... 50

1988 aerial photography 52
1965 aerial photography 54
1951 aerial photography 55
Rock reefs and stacks 61
Assessment of the cliff top position on the headlands near Gling Glang and Glupein na Drochaide 63
Gling Glang 63
Assessment of the aerial photographic investigation 66
9 **CONCLUSIONS 68**
Coastal Changes 68
Methods 69
The 1955 Dounreay Site Survey 71
Photogrammetric results 71
Summary 73
10 **REFERENCES 74**
11 **GLOSSARY 75**
Appendix A Field Observation Point Data from Foreshore Reconnaissance 76

1. ACKNOWLEDGEMENTS

1 This report and the GIS, including the digitized coastal features, from maps and aerial photography stereoscopic models, and walk-over surveys data was produced by C A Auton, Geology and Landscape, Scotland Programme (BGS Edinburgh). Digital photogrammetry was undertaken by D Tragheim, Spatial Geoscience Technologies Group, BGS Keyworth. Optimisation of the accuracy of Phase 2 stereoscopic aerial photography modelling was enabled by collection of Differential GPS (dGPS) co-ordinates by J Boniface (DSRL) and R MacKellar (Jacobs), under the direction of G Morgan. The project was managed by J D Everest, as a Commissioned Study by the Responsive Surveys Scotland Team under the leadership of H F Barron (BGS Edinburgh) and S D Campbell (Geology and Landscape, Scotland, Programme Manager).

1 In addition to the staff acknowledged above, the considerable efforts of J Bow, Remote Sensing and GIS Support, BGS Edinburgh, provided a major contribution to the construction of the ArcMap GIS output and, in particular, to the successful application of the linked ArcMap/SocetSet software, enabling digital photogrammetry to be undertaken that was fundamental to the production of this report. The assistance of R B Haslam (Keele University) in undertaking the cliff-top position Differential GPS (dGPS) survey in June 2008. Is also gratefully acknowledged.

2 EXECUTIVE SUMMARY

2 This report describes the results of coastal evolution and monitoring studies undertaken in two phases by BGS, between 2008 and 2010. The studies were commissioned by Dounreay Site Restoration Limited (DSRL) with the aim of providing a baseline for evaluating rates of past coastal erosion and for monitoring future erosion around the Dounreay nuclear site in Caithness. The studies involved construction of a GIS which contains digitized datasets of time series of coastal features derived from 1: 2,500 scale OS mapping, a dGPS survey, a walkover of the coastline seaward of the DNPE and analyses of georectified stereoscopic aerial photography using SocetSet® software. It also includes topographic surveys and other datasets provided by DSRL. The GIS database contains some 912 files.

3 The first phase of work was focused on the coastline within the NLLW-AOI, specified by DSRL, which extends from near the south western margin of Landfill 42, to the vicinity of Greeny Geo; it covers the ground immediately seaward of the proposed Low Level Waste Facilities to be constructed north east of the current Dounreay nuclear establishment.

4 The second phase of work focused on the coastline within the DS-AOI, which extends from Landfill 42 to the vicinity of Geo Cuinge: it covers the ground immediately seaward of the Dounreay Nuclear Power Establishment (DNPE) Site and RN Vulcan.

5 The positions of the coastal cliff top, High Water Mark and Low Water Mark were digitized in ArcMap 9.2 from georectified Tagged Image File Format (.tif) images from four vintages of OS topographic base maps, spanning surveys conducted between 1872 and 1986. Cliff top positions, rock reefs and stacks recognised on stereoscopic images from four sorties of historical aerial photography, flown in 1951, 1965, 1988 and 2004 were also digitized.

6 The study has highlighted the limitations in assessing the detailed evolution of the Dounreay coastline using historic OS datasets alone, and, although four vintages of mapping were available, it became apparent that full surveys were only conducted in 1872 and 1966/67. Georectification discrepancies of ± 5m were commonly present between the individual survey tiles. No meaningful direct comparison could be made of High Water Mark or Low Water Mark positions between the 2 surveys, because of changes in the Ordnance Datum used prior to and post 1921. Direct comparisons could however, be made of the interpreted position of the cliff top, even though these changes are affected by alterations in cartographic ornamentation used to depict the coastline on the different vintages of map.

7 Georectified imagery of topographic mapping of the Dounreay area, conducted in 1955 was also examined. Cliff top position, the interpreted base of superficial deposits and the location of cliff line gullies were digitized from this dataset which shows the coastline prior to the construction of the DNPE and RN Vulcan. Within the DS-AOI, the position of the cliff top shown by this survey typically lies tens of metres landward of its position shown on the later OS maps; its position is comparable to that seen on the 1951 aerial photography.

8 The most evident changes of coastline morphology occur within the DS-AOI, where the present day cliffs are cut into unconsolidated deposits. These have been eroded in places to the extent that, for example, the cliff top position in the vicinity of [^{2}9921 ^{9}6785] on the 1872/1906 maps is up to 18 m landward of its position on the 1966/1982 maps. This scale of change in cliff position is too great to be merely as a result of geo-rectification differences and indicates that this portion of the cliff has moved seaward as a result of tipping of spoil over the natural cliff edge.

9 Man made materials that were present within the superficial deposits capping a stack at [^{2}99810 ^{9}67533] show that modification of the cliff line has clearly taken place in that area since the 1980's and may be ongoing. Terrestrial LiDAR scanning is recommended for this small part of the coastline to actively monitor the future rate of change.

- The walkover reconnaissance survey conducted in September 2009 indicated that, apart from a small area in the vicinity of Dounreay Castle, none of the superficial deposits are *in situ* within the DS-AOI. The deposits which resemble glacial till that has been bulldozed or tipped into its present position during construction of the DNPE and RN Vulcan sites. It contains building debris and rock fragments and is much less consolidated than typical tills in the region. Consequently, its resistance to erosion is likely to be much less than undisturbed tills in the area and inferences on erosion rates, based on evidence from cliffs in undisturbed glacial deposits should therefore not be applied to most of the cliff line within the DS-AOI.

10 In the NNLF-AOI, most of the cliffs are cut predominantly in bedrock. Where the rock cliffs are steep, any cliff recession generally appears to have been slight. If recession has taken place it cannot be accurately ascertained from the OS mapping as any apparent change of position falls within, or close to, the georectification error between the datasets. Consequently rates of erosion of 10–50 mm pa, postulated by Hutchinson *et al.* (2002) [1], cannot be resolved from the 1: 2,500 scale topographic maps.

11 The larger amounts of coastal erosion in the vicinity of Oigin's Geo, Geodh nam Fitheach and Glupein na Drochaide that were postulated during Phase 1 of this study now appear erroneous. New aerial photography from 1965 and 2004, improved calibration of all of the photographic models, and very detailed assessment of the morphology of ground shown on these models, indicate that very little modification of the cliff line has occurred since 1951.

12 Although there were difficulties in processing the scans of historic air photographs and constructing the SocetSet stereographic images, the resulting imagery is generally of high quality; the digital orthorectified 2004 colour imagery is outstanding. The latter, in particular, provides a much more accurate model of the coast than the topographic maps. Comparison of the datasets provided by the photography flown in 1951 and 2004 produced the most important and accurate data on cliff top evolution in both Areas of Interest. Cliffs with irregular vertical and lateral profiles, cut in unconsolidated materials are evident in the DS-AOI on both sets of images, as are the rocky steep cliffs in the Area of Interest.

13 In general, the results of these studies indicate that, apart from parts of the cliff line developed in man-made deposits, seaward of the DNPE and RN Vulcan

sites, the coastline at Dounreay appears to have been subject to only gradual change during the last 137 years. There is no unambiguous evidence of noticeable recession of the natural cliff line within either Area of Interest and, at the normal scale of field survey (1: 10,000) employed by BGS, the surveyed position of the 'natural' cliff top would be comparable to its position at the time of the first 1872/1906 OS surveys. Future monitoring of the coastline modification should be considered however, when new georeferenced digital stereoscopic aerial photographic coverage becomes available, as it would be a very simple and cost-effective means of building upon the baseline presented here.

3 INTRODUCTION

14 This report is the published product of a coastal evolution and monitoring study, commissioned by DSRL, formerly the United Kingdom Atomic Energy Authority (UKAEA) Dounreay. The study was undertaken in response to Framework Agreement No. SFA055/07 'Provision of Geographical Information System and scoping study to assess the applicability of remote sensing techniques' (Task Order Number 3100014351), between DSRL and the British Geological Survey (BGS), dated 09 October 2008. It is based upon a proposal for commissioned studies for coastal evolution monitoring, submitted to DSRL by BGS on 17 July 2008, covering creation of a Geographical Information System (GIS) containing digitized datasets of time series of coastal features (cliff top position, High Water Mark and Low Water Mark) from large-scale Ordnance Survey (OS) mapping and time series of cliff top positions digitized from georectified stereoscopic aerial photography. These studies, undertaken by C A Auton (BGS, Edinburgh), form part of the work programme for monitoring coastal evolution for the Dounreay area proposed in a desk study by Auton *et al*., 2007 [2], submitted to the United Kingdom Atomic Energy Authority, Dounreay (UKAEA, Dounreay) in September 2007.

15 The Dounreay Nuclear Licensed Site is being decommissioned by DSRL. This has required a strategy for the long-term management of Dounreay's low level waste disposal in new shallow below-surface facilities. These New Low Level Waste Facilities (NLLWF) are to be constructed on land owned by the Nuclear Decommissioning Authority (NDA) inland of the coast, north east of the current nuclear establishment. In 2007, DSRL employed BGS to undertake two projects relating to the evolution of the coastal zone seaward of the proposed NLLWF disposal site:

- To undertake a desk top review of previous research on coastal evolution scenarios for the Dounreay site area.
- To prepare a report for new and innovative methods of coastal evolution monitoring.

16 The review of previous research and a suggested range of techniques for coastal evolution monitoring, were presented at an on-site meeting and reconnaissance visit by BGS staff to Dounreay on the 09-10 July 2007. DSRL's New Low Level Waste Facilities Area of Interest (NLLWF-AOI) was identified (Figure 1). The applicability of each approach was assessed in BGS Open Report OR/07/017, 'Desk review of coastal erosion studies at UKAEA Dounreay' (Auton *et al*., 2007) [2], which also reviewed the methods used in previous studies of coastal erosion rates in the Dounreay Site area.

17 A meeting between DSRL and BGS in Edinburgh, in early May 2008, reviewed the applicability of the methods suggested by BGS, which fell into two principal categories:

1. Remote sensing and digital data integration
2. Field and laboratory survey and testing

18 Following the meeting, a request was submitted, by e-mail from Michael S Tait (DSRL) on 12 May 2008, for a detailed proposal to undertake the following investigations:

1. Creation of a GIS to include a historical sequence of georectified aerial photographs and large-scale topographic maps to show a time series of cliff top and foreshore positions
2. Differential survey of the cliff top position and sample sites
3. Geological survey and Rock Strength (Schmidt Hammer testing & geotechnical sampling)
4. Lichenometry
5. Geotechnical testing (Slake Durability test, Universal Compressive Strength test)
6. Petrological analysis of the lithologies sampled for geotechnical testing
7. Laser scanning (terrestrial LiDAR)

19 After further discussions between DSRL and BGS it was agreed that remote sensing and integration of past topographic survey data with a GIS was the most cost effective method of providing a baseline of past coastal erosion rates covering the last 100 years.

20 This would involve creation of a GIS to include assessment of historical sequences of georectified air photographs and large-scale topographic maps, to show a time series of cliff top and foreshore positions.

21 Following further discussions between BGS and DSRL regarding the scheduling and the perceived utility of each of the investigative techniques, a Frame Work Agreement was set up between DSRL and BGS. This established that the initial work by BGS would begin with some elements of BGS's original proposal to DSRL of 07 July 2008 i.e. creation of an Arc 9.2 GIS containing suites of digitized time series of baseline data of coastal positions. These were to be derived from large-scale OS mapping, digital photogrammetry of stereoscopic models from aerial photography, and a dGPS survey of the current cliff top position seaward of the NLLWF-AOI.

22 The Framework Agreement also included a work instruction to produce a feasibility study to process European Space Agency (ESA) satellite datasets and evaluate the applicability of PSInSAR™ (Permanent Scatterer Interferometric Synthetic Aperture Radar) methodology to assessing ground and coastline stability on both a local (Site) and regional scale. The results were published as part of BGS Commissioned Research Report CR/09/11, [3] submitted to DSRL in March 2009.

23 A second area of work was also commissioned; a desk study to evaluate the suitability of Permanent Scatterers Interferometry Synthetic Aperture Radar (PsInSAR) observations, to supplement ground-based monitoring of the coast around Dounreay with radar satellite observation.

24 Following the successful completion and reporting of these initial phases of work, a meeting was held between DSRL representatives and BGS staff, at Dounreay on 24 April 2009. This agreed to scope a second phase of work to be commissioned. An invitation to tender for this second phase of work was received by BGS on 06 July 2009 and it commenced, on receipt by BGS of Consultancy Agreement No. 3100020816, from DSRL, on 10 August 2009. The integrated results of both phases of work are presented here in the form of a Final Interpretation Report

25 The second phase of commissioned work extended the coverage of the GIS to the south west, to include foreshore seaward of the DNPE. In particular it encompassed the foreshore between the south western margin of the NLLWF-AOI at [^{2}992 ^{9}678] and Geo Cuinge [^{2}977 ^{9}667]. This is the Dounreay Site–Area of Interest (DS-AOI), as defined by DSRL (Figure 1). The second phase study also included revisiting and extending the evaluation of the Phase 1 photographic and topographic datasets to include more foreshore geomorphic features, such as the extent of sea stacks, digitising coastal features from the Dounreay on-site 1955 topographic survey. It also involved completion of aerial photography stereoscopic models for both the NLLWF-AOI and Dounreay Site-Area of Interest (DS-AOI). It also included evaluation newly available (Getmapping®) digital colour aerial photography from 2004 for both Areas of Interest.

26 The photogrammetric methodology employed was adapted and refined from that used in the Phase 1 study, in order to address some of the problems of georectification encountered during the earlier work. In particular, 3D georectification of the historic aerial photographic data sets was enhanced by the collection of new dGPS data, for specific sites selected by BGS that are present in the landscape today, and which were present and visible on the historic photographs.

27 A walk-over reconnaissance of the foreshore between Landfill 42 and Geo Cuinge was also undertaken to investigate the materials that form the present day cliffs between the south western margin of the NLLWF-AOI and Geo Cuinge.

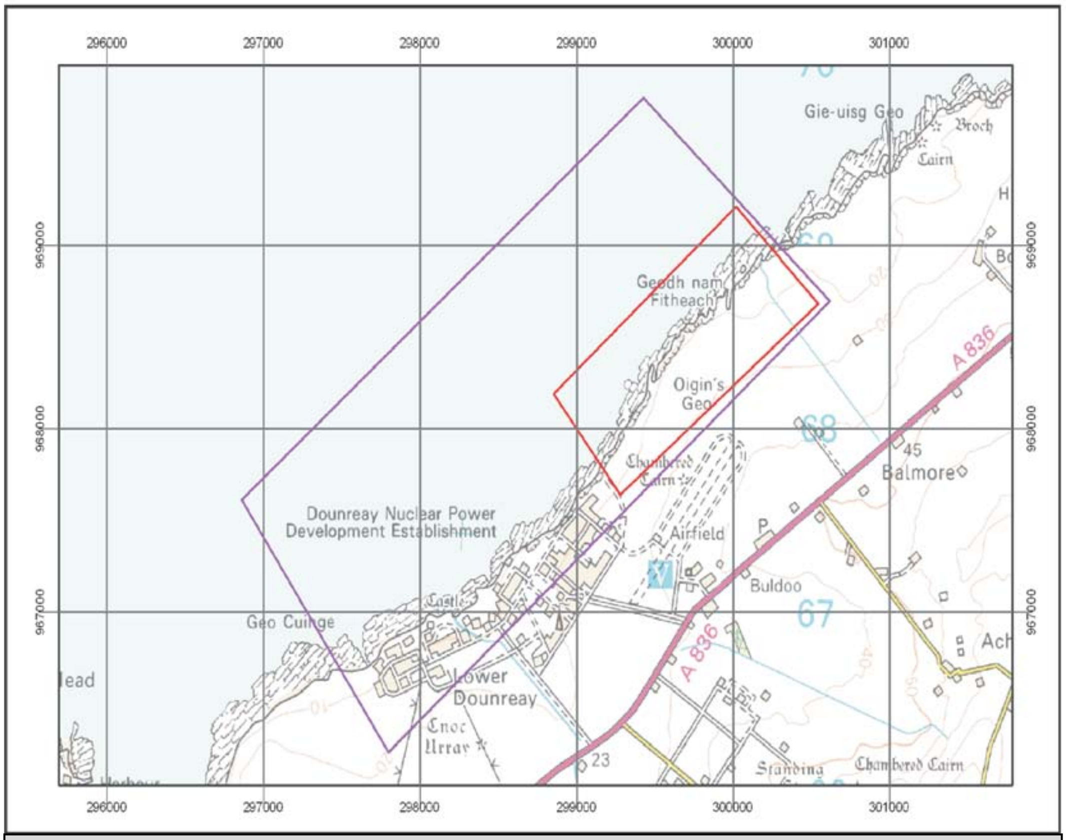


Figure 1. Location of DSRL Areas of Interest. NLLWF-AOL shown in red outline, DS-AOL in purple outline.

4. GIS CREATION (REMOTE SENSING AND DIGITAL DATA INTEGRATION)

Aims

28 The aims of this task were to establish a baseline dataset for the present morphology of the coast for both of DSRL's Areas of Interest (Figure 1). This involved creation of a time series of the evolution of the coastline (in particular the position of the cliff top) from two existing large-scale datasets: vertical aerial photographs and historical large-scale (1: 2,500) OS maps. It included a dGPS survey of the cliff top position within the NLLWF-AOI, conducted in June 2008. This provided absolute values of the height and position of the cliff top. It was used to constrain the accuracy of the cliff top line digitized from the maps and aerial photographs within the NLLWF-AOI area.

29 The first phase of this work, which was reported on 23 March 2009, produced a fully attributed GIS containing the digitized positions of the coastal features, derived from the OS maps and aerial photographs. This covers the foreshore and cliff line along the coast between British National Grid Reference (NGR) [^{2}988 ^{9}673] and [^{3}004 ^{9}691]. This corresponds with the coastal zone within the New Low Level Waste Facilities Area of Interest (NLLWF-AOI) as specified by DSRL.

30 The GIS was created in ArcMap 9.2© Environmental Systems Research Institute (ESRI). The cliff top positions on stereoscopic aerial photographs were digitized using SocetSet® V5.4.1 software, linked to ArcMap, under Commercial License Agreement No. ea3f6954 between BAE Systems Geospatial eXplotation Products ™ and the Natural Environment Research Council (NERC). The SocetSet software enables viewing of stereographic models of georectified digital aerial photographic imagery, enabling digitization and geospatial analysis of features and elevations in either two or three dimensional (2D or 3D) ground space to create precise geodatabases. Three dimensional geodatabases require the inclusion of a Digital Elevation Model (DEM) within the SocetSet project. The DEM used to produce elevation values for the cliff top positions from the Digital colour aerial photographs, and the georectified 1988 monochrome imagery was derived from NEXTMap Britain Elevation data (©Intermap Technologies) at 5 m vertical and horizontal resolution (NEXTMap® End User License Agreement between Intermap Technologies Inc. and NERC Contract 2K05A047) flown in 2003-4. The NEXTMap DEM was considered to be unsuitable for deriving elevations for the cliff top positions recognised on earlier (1951 and 1965) historic aerial photographic datasets (due to possible degradation of the cliff top by erosion). Consequently, the cliff top positions recognised on this earlier photography were digitised as 2D lines.

31 Meta-data, as .xml files to ISO 19115 standard, were generated for all vector and raster datasets generated by BGS, as required by the 'Specification for provision of GIS data by a contractor' Operating Instruction GIS/OI/011, supplied by DSRL

32 The first phase of study also included a Differential GPS (dGPS) survey of the cliff-top position, in June 2008, conducted by C A Auton and R B Haslam (Keele University).

33 The position of the cliff top within both of DSRL's Areas of Interest, covered by the 1: 500 scale 1955 Dounreay Site survey, was digitized during the Phase 2 study, as were the Field Observation Points (FOP's) visited during the walk-over reconnaissance of the foreshore within the DS-AOI in September 2009. The results of these studies were integrated in the ArcMap 9.2 GIS, suitable for incorporation into DSRL's GIS.

Map and aerial photography datasets

34 In consultation with OS and Landmark®, it was established that four series of 1: 2,500 scale topographical maps were available covering both Areas of Interest (1872, 1906, 1966/67, 1982/86); see Table 1.

35 Consultation with DSRL established that seven vintages of stereo-pairs of vertical air photographs were initially available for the Phase 1 study; an eighth set of stereoscopic photographs, supplied as colour .tif files by Getmapping®, were included in the Phase 2 study (Table 2). The baseline established from OS mapping would highlight any significant changes to the cliff top position identified by survey mapping between 1872 and 1982. It was envisaged that the baseline established from aerial photography would cover coastal evolution within the DSRL-AOI and, in particular, identify whether or not significant (large-scale) changes to coastal morphology have occurred between 1946 and 2006.

36 Most of the map data were supplied by the Ordnance Survey as georectified .tifs; some was supplied by DSRL, also as georectified .tifs. Georectification of all the aerial photographs was undertaken by BGS, apart from the Getmapping® imagery for 2004, which were supplied as georectified images (see below).

OS 1:2,500 scale topographic data sets examined	
Tile Name	**Year**
National Grid Series (Map Rasters)	
NC9867.TIF - Epoch: A5	1966
ND0068.TIF - Epoch: A5	1966
NC9967.TIF - Epoch: A5	1966
ND0069.TIF - Epoch: A5	1967
NC9968.TIF - Epoch: A5	1966
NC9766.TIF - Epoch: A5	1966
NC9866.TIF - Epoch: A5	1966
National Grid Survey Information on Microfiche (SIM)	
NC9867SM1.TIF - Epoch: SIM 1	1982
NC9967SM1 TIF- Epoch: SIM 1	1982
NC9766SM1 TIF Epoch: SIM 1	1986
All Tifs supplied georectified by OS	
County Series (Supplied by DSRL, Dounreay)	
OS_2500_1906.TIF	1906
OS_2500_1872.TIF	1872
Tifs georectified by DSRL, Dounreay	

Table 1. Ordnance Survey large-scale topographic maps; Phase 1 coverage ~ roman; Phase 2 ~ italic.

Stereoscopic aerial photography examined				
Source	**Sortie**	**Scale**	**Images**	**Year**
RAF	*CPE/SCOT/UK 185*	*1:25,000 (approx)*	*1197-1199*	*1946*
RAF	**540/RAF/506**	**1:24,000 (approx)**	**3057-3063**	**1951**
RAF	543/RAF501	1:10,000 (approx)	30-31	1959
OS	**OS/65/062**	**1:10,000 (approx)**	**016-022**	**1965**
OS	OS/71/115	1:8,000 (approx)	001-005	1971
Clyde Surveys	Scottish Coastal Survey 7343	1:10,000	38 607-608	1975
RCAHMS*	**60888**	**1:24,000**	**226b, 227b-228, 229**	**1988**
Getmapping	**GMSCOT04**	**1:12,000 (Digital)**	**606/004-009; 081-084;222-225**	**27/5/2004**

*** Royal Commission on the Ancient and Historical Monuments of Scotland.**

Table 2. Phase 1 and Phase 2 aerial photographic datasets.

5 DIGITISATION OF OS MAP DATA

37 Digital shape (polyline .shp) files were produced, using ArcMap 9.2, for each topographic dataset. These were:

- The mapped positions of the cliff top/cliff edge
- Mean Low Water Spring Tides (MLWS), or its nearest equivalent on the 1906 and 1872 map bases
- Mean High Water Spring Tides (MHWS), or 'High Water Mark of Ordinary Spring Tides' on the 1906 and 1872 map bases

38 Digitising was undertaken at 1: 1,000 scale, giving a resolution of 1 mm to 1 m. Over 1,000 points were generated during the digitization of each 'complete' polyline that covered both AOI's. Each 'complete' polyline is typically c. 6.5 km in length, giving a digitizing interval in the order of 1 digitized node per c. 6.5 m; comparable intervals were achieved for polylines that only cover portions of the AOI's. An example, showing the positions of the cliff top and MLWS from the 1966/67 map is shown as Figure 2

General evaluation of the 1: 2,500 scale topographic bases

39 The .tifs of the 1872 [OS_2500_1872] and 1906 [OS_2500_1906] topographic bases are identical, except in the clarity of reproduction of their line work (with the 1906 edition superior). This was confirmed in the ArcMap project, by applying a 50% transparency to the 1906 data and an inverted green Colour Ramp to the 1872 data, and then superimposing the 1872 .tif on the 1906 .tif (see Figure 3). A relative offset, typically of 4–5 m, was measured between given lines on each dataset. The amount of offset varied across the datasets, but, in general the raster of the 1906 map is displaced south eastwards (shore-wards) from the raster of the 1872 map. It is clear that no resurvey of the coastline was undertaken between the two dates and any apparent differences between the positions of the cliff top, 'Possible Low Water Mark' and 'High Water Mark of Ordinary Spring Tides' (as identified on these map editions) are due to variation in the accuracy of georectification between datasets.

40 The single 1967 georeferenced tile (ND0069,TIF) abuts adjoining 1966 tiles without any apparent discrepancy and they thus form a single surveyed group of 1966/67 data. Two tiles: NC9766.TIF - Epoch: A5 and NC9866.TIF - Epoch: A5, were added to the 1966/67 dataset during the second phase of this study (see Table 1). This completed the coverage for the DS-AOI, which was total, apart from a small portion of foreshore between MHWS and MLWS in National Grid square [NC 9767] which is not available.

41 The positions of the cliff line, MLWS and MHWS on each OS tile have been digitized separately, but they have been evaluated as a group, in comparisons made between the 1966/67 tiles, the 1872 and 1902 mosaic-ed data ,and the data from the 2008 dGPS cliff top survey (see below).

42 No additional tiles were available from the 1982 OS topographical survey, but a single tile, NC9766SM1 TIF Epoch: SIM 1, was produced in 1986. This extends the coverage of the most recent OS survey data southwestwards along the coast to beyond Geo Cuinge. This tile, together with the two from the 1982 survey (see Table 1; Phase 1 and Phase 2 coverage) gives an almost

continuous coverage of the foreshore adjacent to the DNPE site and is treated here as a combined 1982/86 dataset.

43 Where tifs of the 1966/67 and 1982/86 topographic bases coincide, they are often almost identical. The similarity between the 1966 and 1982 topographic bases was again confirmed by applying a 50% transparency and an inverted green Colour Ramp to the data and superimposing the .tifs. A relative offset, typically of c. 2–7 m, was measured between given lines on each dataset. Again, the amount of offset varied across each dataset but, in general, the rasters of the 1966/67 maps were displaced southwards (shore-wards) from the rasters of the 1982/86 maps.

44 The sum of the relative displacements between the 1966/67 and 1982/86 topographic bases were smaller than that between the 1872 and 1906 datasets; but almost all of the apparent differences between position of the cliff top, MLWM and MHWS are again due to variation in the accuracy of georectification between both of these recent datasets, rather than actual morphological changes to the coastline. It is also clear however, that a limited amount of resurveying took place and was incorporated in the 1982/86 mapping. This surveying focused on the DNPE site itself, with changes to the disposition of many of the buildings, other infrastructure and constructions on the foreshore, such as jetties and pipelines, being evident between the 1966/67 and 1982 survey dates.

45 There are obvious difficulties in trying to compare changes in MLWS and MHWS (as identified on the 1966/67 and 1982/86 map editions) with 'Possible Low Water Mark' (as identified on, or interpreted from, the 1872 and 1906 maps). The first difficulty, is that the definition of Ordnance Datum (OD) used by the Ordnance Survey (Harley, 1975 [4]; Close *et al*., 1922 [5]), and hence its relationship to MLWS and MHWS, has changed over time:

- At present, Ordnance Datum (OD) for the Ordnance Survey is ODN (Ordnance Datum Newlyn), defined as the Mean Sea Level (MSL) at Newlyn, in Cornwall, between 1915 and 1921.
- Prior to 1921, OD was taken from the level of the Victoria Dock, Liverpool This is known as the 'Liverpool Datum'. The original datum, or zero point level, was 100 feet below a bench mark bolt on St. Johns Church in Liverpool, chosen in 1841.
- In 1844, an alternative datum was adopted at Victoria Dock, Liverpool. This controlled Ordnance Survey levelling until Ordnance Datum Newlyn was adopted in 1921.

46 Another difficulty is that the Low Water Mark position on the 1872 and 1906 surveys is interpreted from the OS topography (it is not identified specifically on the map face); a different, but comparable problem is that the concepts of 'High Water Mark of Ordinary Spring Tides' and MHWS may be similar, but they are not identical.

47 All of these constraints mean that comparisons between the 'High Water Mark' and 'Low Water Mark' positions across the time series of OS maps are limited (see below).

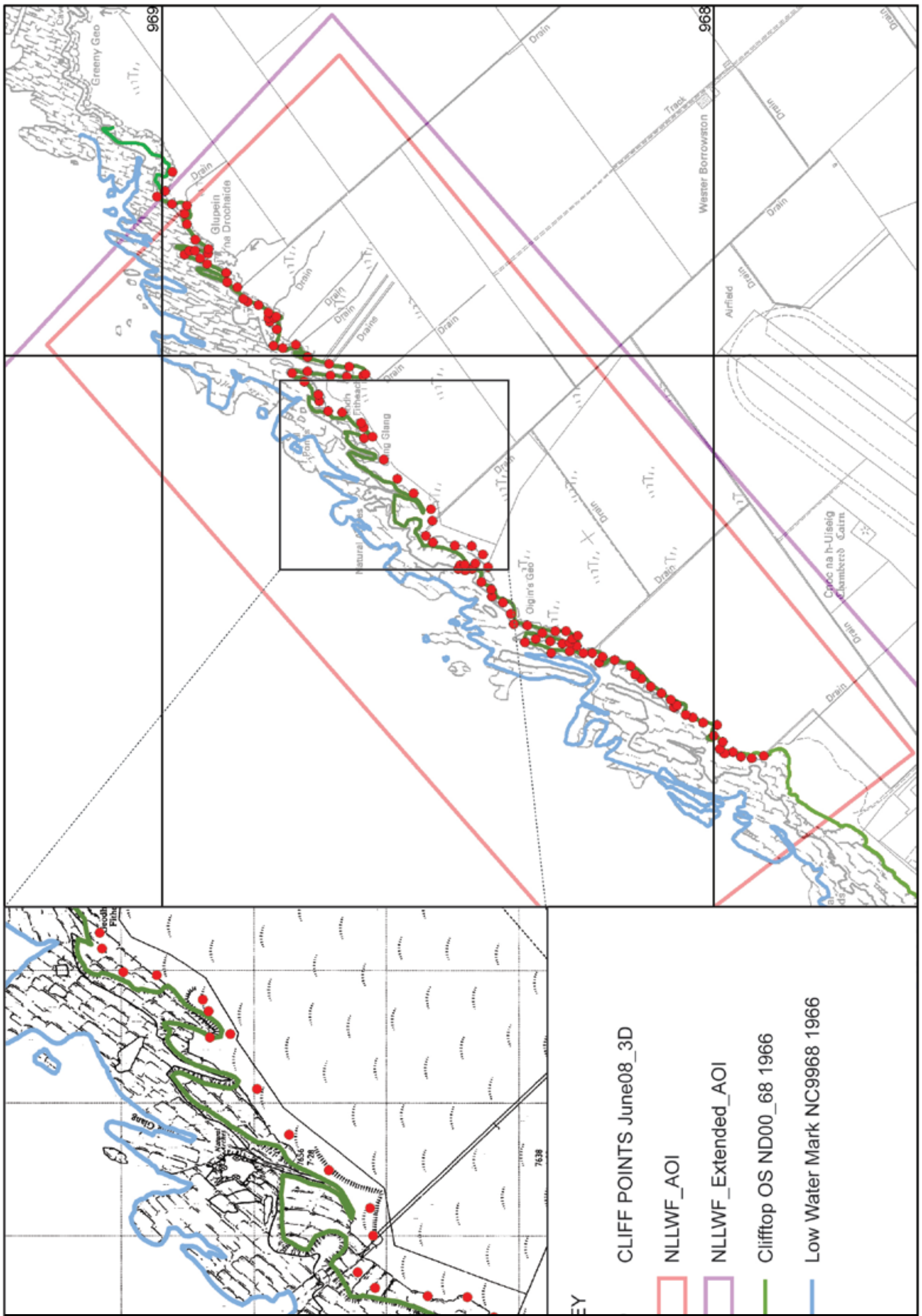


Figure 2. The positions of the cliff top and MLWS between [^{2}9980 ^{9}6730] and [^{3}0040 ^{9}6910] from the 1966 map and the dGPS points on the cliff top surveyed in 2008.

Inset shows portion of coast where the 2008 dGPS cliff top points occur a significant distance inland of the 1966/67 position of the cliff line, indicating a possible area of cliff recession.

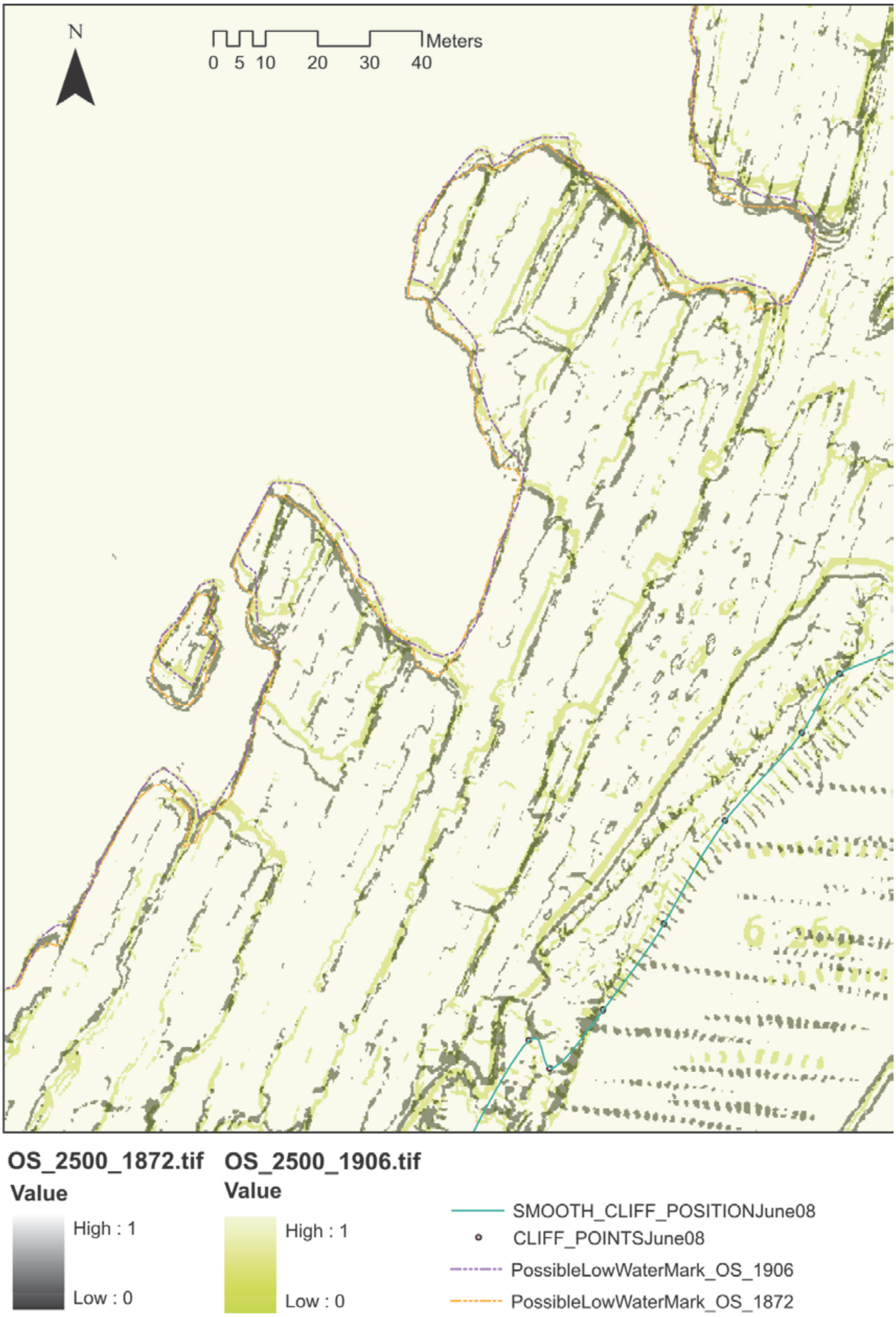


Figure 3. Colour ramp showing the offset between the georectified OS 1872 and 1906 topographic base maps.

Results

48 The shape files generated from digitising the coastal features derived from the OS maps were each grouped in folders:

1. **Cliff_Top_POSITIONS_MAPS**

This contains 12 .shp files, each digitized from the 12 topographic maps:

- ClifftopOSNC98_67.shp
- ClifftopOSNC98_67SM1.shp
- ClifftopOSNC991968.shp
- ClifftopOSNC99_67.shp
- ClifftopOSNC99_67SM1.shp
- ClifftopOSND001968.shp
- ClifftopOSND00_69.shp
- OS1872_2500.shp
- OS1906_2500.shp
- ClifftopOSNC97_66_1966.shp
- ClifftopOSNC9866A5_1966.shp
- ClifftopOSNC9766SM1_1986.shp

2. **Mean_High_Water_mark_POSITIONS**

This also contains 12 .shp files, each digitized from the 12 topographic maps:

- HighWatermark of OrdinarySpringTides_OS_1872.shp
- HighWatermark of Ordinary SpringTides_OS_1906.shp
- MHWSNC9967_1966.shp
- MHWSNC9968_1966.shp
- MHWSND0068_1966.shp
- MHWSND0069_1967.shp
- MHWS_NC9867SM1_1982.shp
- MHWS_NC9967SM1_1982.shp
- MHWMNC9867_1966.shp
- MHWSNC9866A5_1966.shp
- MHWSNC9766A5_1966.shp
- MHWS_NC9766SM1_1986.shp

3. Mean_Low_Water_Mark_POSITIONS

This contains 12 .shp files, each digitized from the 12 topographic maps:

- LowWaterMarkNC9867.shp
- LowWaterMarkNC9867SM1.shp
- LowWaterMarkNC9967.shp
- LowWaterMarkNC9967SM1.shp
- LowWaterMarkNC9968.shp
- LowWaterMarkND0068.shp
- LowWaterMarkND0069.shp
- LowWaterMarkNC9866A5_1966.shp
- LowWaterMarkNC9766A5_1966.shp
- Low WaterMarkNC9766SM1_1986.shp
- PossibleLowWaterMark_OS_1872.shp
- PossibleLowWaterMark_OS_1906.shp

Interpretation of the results – NLLWF-AOI and DS-AOI

Cliff Top/Cliff Edge Positions

49 Although the cliff top positions are digitized interpretations from the OS topographic maps (rather than shown specifically by OS on the map faces), they are not subject to the constraints on MHWM and LHWM outlined in paragraph 46 above. They are therefore the only lines that can be directly compared across the whole time series of the OS map data.

50 The digitized positions of the cliff top on the 1872 and 1906 maps are almost identical; any minor differences relate to variations in georectification accuracy between the 2 datasets and minor changes in cartographic symbolisation between the two editions.

51 The digitized positions of the cliff top on the 1966/67 dataset (and on the 1982/86 surveys) indicate minor local changes relative to the 1872 and 1906 data. The most obvious are along the cliff top in front of the DNPE site and Landfill 42, and the existing LLWP. Here the cliff top is underlain by unconsolidated deposits (principally made ground). The 1872 and 1906 surveys suggest that the cliff top in the vicinity of [^{2}9916 ^{9}6781], immediately adjacent to Landfill 42, was some 20m seaward of the position suggested by the 1966/67 and 1982/86 maps. This ground lies within both the NLLWF-AOI and the DS-AOI. This change in position of the cliff top adjacent to Landfill 42 (relative to its position on the 1872 and 1906 maps) is probably due in large part to former extraction of flagstones in a small quarry immediately to the east of the landfill (see Figure 4). Parts of this quarry are clearly visible on the stereoscopic aerial photographic imagery, but it is also apparent that some of the south western portion of formerly worked ground is concealed beneath the landfill material.

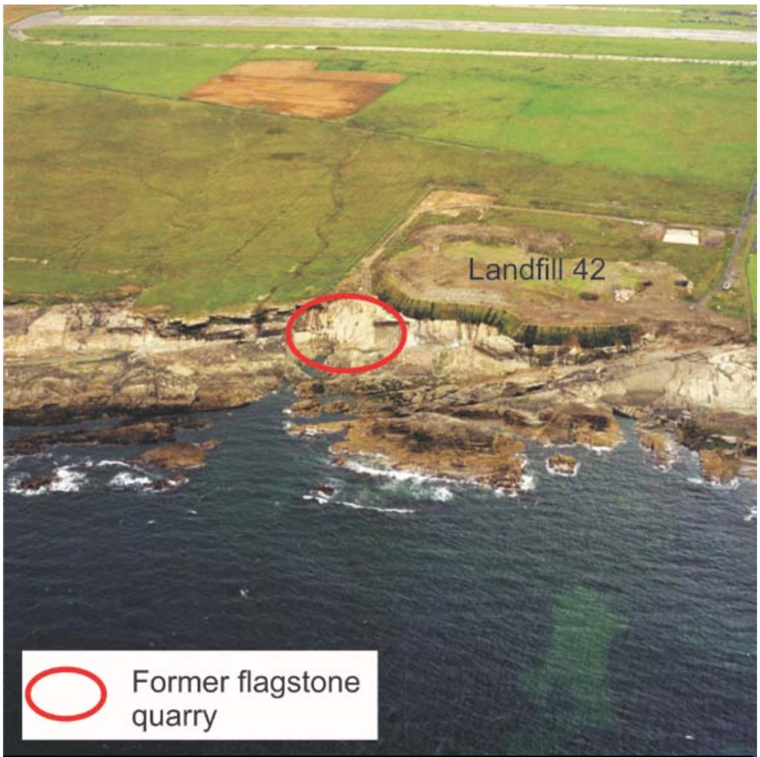


Figure 4. Oblique aerial photograph taken in 1997 showing the position of former flagstone quarry below cliff line near SW margin of the NLLWF-AOI (supplied by G Morgan, DSRL).

52 Some other changes in position of the cliff edge may be more apparent than real. A proportion of the apparent change may be due, in part, to differences between the ornaments used to indicate the cliff top position on the earlier maps (where the cliff was unmodified by the presence of the made ground associated with the LLWP) and later maps (where Landfill 42 is shown as a 'spoil heap' adjacent to the LLWP area). Elsewhere, small real changes may be a result of erosion of the glacial till and man-made deposits in the 60 years between surveys (1906–1966 minimum interval).

53 In contrast, a distinct cliff edge is shown on the 1906 and 1966 rasters in the vicinity of [^{2}9913 ^{9}6775]. It is coincident with the natural cliff position on the 1872/1906 maps, but it is absent on the 1982 raster. The digitized position of the cliff top in this locality is similar for all of the time series (1872–1982), suggesting little landward migration of the cliff, but the change in ornamentation suggests that between the times of the 1966 and 1982 surveys, the cliff may have formed in man-made rather than natural materials, due to tipping in this small area. This is supported by the mapped extent of the 'Spoil Heap' on the 1982 raster. It is shown as occurring seaward of the cliff line position digitized from all of the OS surveys; suggesting that the cliff was being cut into tipped material at the time of the 1982 survey. The walkover coastal reconnaissance survey, conducted in September 2009, showed this area of foreshore is now free of spoil (see below).

54 Within most of the remainder of the NLLWF-AOI, the positions digitized for the cliff top are almost coincident for all of the datasets available (1872, 1906,

1966/67) and any discrepancies lie within the range of georectification errors for the raster images. Exceptions occur however, for example on the small promontory to the west of Oigin's Geo [^{2}9949 ^{9}6827] and on the cliff on the eastern side of the Geo. In places on the headland, the 1966 cliff top line occurs between 4m and 8m landward of the 1872 and 1906 positions; similar displacements also occur on the eastern cliff. Although small, these combined offsets of the cliff top suggest that parts of the Geo may have widened by more than 10 m in the intervening 60 years (1906 - 1966); it could be argued that the time interval should be regarded as being 94 years (1872 – 1966) as the 1872 and 1906 topographic bases are apparently almost identical. The 1966 cliff top position shows good general agreement with the data from the 2008 dGPS survey, indicating that the digitized 1966 line is probably a fairly accurate reflection of the cliff position at that time. On the other hand, it also suggests that little measureable cliff recession has occurred in the 42 years between the 1966 OS survey and the 2008 dGPS survey.

55 The apparently conflicting possible interpretations for one small area of the coast, presented above, show how difficult interpretation of the historic OS datasets is, and how limited the reliability that can be placed on any set of measurements. It is possible that significant changes have taken place, such as the collapse of portions of the cliff face, but it seems that these are local events; the datasets show no unequivocal evidence of large-scale uniform cliff recession. Further detailed study of past cliff line positions form the exiting aerial photography

56 Within the DS-AOI, significant seaward displacement of the cliff top position digitized from the 1966/67 OS rasters (and from the almost identical 1982/86 dataset), relative to its position shown on the 1872/1906 surveys, is evident in many instances:

1. The 1966/67cliff top position lies c.35 m seaward of its 1872/1906 position in the vicinity of [^{2}9854 ^{9}6758].
2. The 1966/67cliff top position lies c.16 m seaward of its 1872/1906 position in the vicinity of [^{2}9887 ^{9}6749].
3. The 1966/67cliff top position lies up to c.31 m seaward of its 1872/1906 position between [^{2}9874 ^{9}6735] and [^{2}9865 ^{9}6735].
4. The 1966/67cliff top position lies up to c.37 m seaward of its 1872/1906 position between [^{2}9863 ^{9}6734] and [^{2}9858 ^{9}6729].
5. The 1966/67cliff top position lies c.39 m seaward of its 1872/1906 position in the vicinity of [^{2}9781 ^{9}6686].

57 he 2009 coastal reconnaissance survey showed that tipped material forms the modern cliff top at all of these sites, but this is only differentiated by the ornamentation of the 1966/67 and 1982/86 OS rasters at sites 3 -5 listed above; sites 1 and 2 are shown with an ornament apparently indicating a 'natural' cliff at these localities.

58 A single notable example of the 1872/1906 cliff top occurring seaward of its position on the 1966/67 OS mapping is present within the DS-AOI. This occurs in the vicinity of [^{2}9881 ^{9}6741]. This site is seaward of an extensive spread of tipped material, but it is likely that the cliff top position digitized from the 1872/1906 surveys was in fact a 'natural' cliff' top, which occurred at a lower

elevation than the more recent cliff top that was formed in the tipped material. This indicates that the tipping resulted in a higher cliff landward of the natural cliff, but it did not extend sufficiently seaward to completely bury it.

Low Water Mark Position

59 As explained in paragraphs 46 and 47, there are considerable difficulties in comparing changes in the Low Water Mark positions between the different vintages of OS data. It is clear that no re-survey of the coastline was undertaken between 1872 and 1906 and that any apparent differences in the digitized positions of Low Water Mark on either map are due to inaccuracies in the georectification of the datasets.

60 The difference in the Ordnance Datum used for the pre and post 1921 datasets, is clearly illustrated by the major difference in coastal morphology and the position of MLWS on the 1966/67 data, when compared with the 1872/1906 position. As resurveys for the 1982/86 maps were restricted to the onshore area in the vicinity of the DNPE site, any apparent differences in the digitized positions of Low Water Mark are again due to georectification differences between the datasets. Consequently, no meaningful assessment of changes in Low Water Mark can be made between the 1966/67-1982/86 position and the 1872/1906 position.

High Water Mark Position

61 A similar set of circumstances apply when interpreting the relationship between the position of 'High Water Mark of Ordinary Spring Tides' (as shown on the 1872 and 1906 maps) and the position of MHWS shown on the 1966/67 and 1982/86 maps. The 1872 and 1906 topographic bases are almost identical and the High Water Mark positions are coincident (apart from georectification differences). An identical situation is apparent for the MHWS positions on the 1966/67 and 1982 maps; once again, because different datums were used for the pre and post 1921 datasets, no realistic assessment of changes in High Water Mark can be made between the 1966/67-1982/86 position and the 1872/1906 position.

62 As established in the first phase of this study (Auton *et al.*, 2009) [3], the HWMS data from the 1966/67 and the 1982/86 maps are useful, when they are compared with the digitized cliff top positions from the equivalent maps. In general terms, close proximity between the cliff top and MHWS indicates a very steep to near vertical cliff. Increases in the distance between the two equates to a shallowing of the cliff profile. When cliff top, MHWS and MLWS positions are all in close proximity, a very steep to near vertical cliff that may extend below wave base is indicated; increasing distance between MHWS and MLWS, indicates a widening of the wave-cut platform at the base of the cliff and a general shallowing of the profile of the intertidal zone. These observations would have the potential to provide objective criteria aiding division of the coastal zone into areas of characteristic coastal morphology if subsequent more detailed study and monitoring of erosion rates were to be required.

6 ADDITIONAL TOPOGRAPHIC DATASETS SUPPLIED BY DSRL DURING THE PHASE 1 STUDY

63 Five additional pre-existing digital datasets were supplied to BGS by DSRL and are incorporated in the GIS:

- **Site_Topo_Survey_1996_0.shp** (dGPS surveyed points within the On Site area)
- **Off_Site_Topo_Survey_2000_0.shp** (dGPS surveyed points within the Off Site area)
- **Site_Topo_Contours_0.shp** (contours at 1 m intervals constructed, in 2000, from dGPS data from both the 'On Site' and 'Off Site' surveys)
- **Dounreay_Site_Survey_c1955_0.lyr** (This layer file contains 34 scanned georectified .tif images of line drawn plans of an onshore site survey, conducted in 1955. This covered the original airfield at Dounreay and much of the ground between the present DNPE and Sandside Bay to the south west)
- **Coastal_Erosion_Markers_data.shp** (This was a spreadsheet, subsequently converted by BGS into a .shp file, with X–Y co-ordinates showing the positions of DSRL erosion marker positions along the coast within the DS-AOI)

64 These datasets were included within the GIS constructed for Phase 1 of this study principally for completeness, but also to enable future comparisons to be undertaken between this pre-existing topographic and coastal monitoring information and the interpretations presented in the earlier report.

65 The Site_Topo_Survey_1996 data falls largely within the DS-AOI, south west of the NLLWF-AOI, though it impinges on the south western corner of the former. It covers much of the DNPE. The Off_Site_Topo_Survey_2000 extends north eastwards to cover much of the south western half of the NLLWF. It also covers part of the foreshore and hinterland shoreward of RN Vulcan. The Site_Topo_Contours are derived from merging both dGPS datasets and cover both On Site and Off Site areas.

66 Of the five datasets, the Dounreay 1955 Site Survey, which was conducted before the present nuclear facilities were constructed, was the most pertinent for the Phase 1 study of the NLLWF-AOI. The ground covered exceeds that of the subsequent On Site (1996) and Off Site Surveys and includes most of the NLLWF-AOI, apart from its north eastern extremity. It is also the most useful survey of the coastline within the DS-AOI, as the map coverage extends across all of the new ground examined during the second phase of work.

67 The coastal erosion markers dataset was of only minor interest during the study of the coast within the NLLWF-AOI, as all of the data points lie within the DS-AOI; only a few occur adjacent to the southwestern margin of the Phase 1 study area. The potential significance of this dataset increased during the second phase of the study, as the markers are distributed seaward of the fenced-off DNPE ground, between the south western limit of the NLLWR-AOI

and the vicinity of Dounreay Castle. Consequently, the dataset covers much of the coastal zone within the DS-AOI.

Evaluation of the Dounreay 1955 Site Survey

68 The Dounreay 1955 Site Survey was conducted while the ground was an airfield and little of the present infrastructure, apart from the runway, is evident. The survey includes data derived from two distinct sources. The western portion is derived from surveys by W Halcrow, conducted between August 1955 and June 1956; the eastern portion is from surveys by the Land Survey Branch of the Ministry of Works, made between July and October 1954 (both original surveys were conducted at a scale of 1 inch to 44 feet). The topographic data were subsequently incorporated in paper plans, at 1: 500 scale, drafted by UKAEA, Risley (date of drafting not shown). Spot height data were metricated on the paper plans and contours are shown at half metre intervals above Ordnance Datum (AOD). The plans were supplied by DSRL to BGS as 34 scanned and georeferenced overlapping .tifs.

69 Digitisation of the shoreline features from 1955 Site Survey was undertaken as part of the second phase of study and covered the cliff line within all of the DS-AOI and all but the north-western portion of the NLLWF-AOI. Examination of the .tifs showed that the scans were of variable quality. Some images, notably those covering the ground now occupied by the DNPE, were extremely faint, whereas those covering the ground to the south west and north east of the present DNPE were generally much clearer. In most instances, the seaward coverage of the survey extended only to the cliff line, so only attributes related to this feature have been digitized.

70 A folder **UKAEA_1955Surveycliffline_Interpretations** has been created containing three shapefiles:

- **UKAEA_SITE_SURVEY_cliffline_Shapefile.shp**
- **UKAEA_1955SiteSurvey_Interpreted_base_of-superficial_deposits.shp**
- **UKAEA_SITE_SURVEY_Gullies.shp**

71 None of these three features could be digitized along the complete seaward margin of surveyed area, because of variation in the original cartography and the variability of the quality of the scanned imagery.

Cliffline_Shapefile

72 The most easily digitized feature was the cliff line (corresponding in general terms to the ‘cliff top position’ digitized from the OS topographic bases). Even so, this could only be recognised sporadically on survey images covering the south western portion of the NLLWF-AOI; it could not be recognised within the north eastern tiles. Almost complete coverage of the cliff line was possible within the DS-AOI, apart from the cliff between Dounreay Castle [^{2}9832 ^{9}6695] and the former cliff top pumphouse at [^{2}9852 ^{9}6722].

73 The position of the cliff line digitized from the 1955 site survey (shown in orange on Figure 5) and those digitized from the OS maps (1906 ~ magenta; 1966/67 ~ green and 1982/86 shown in blue on Figure 5) show it landward of the position indicated on the OS mapping.

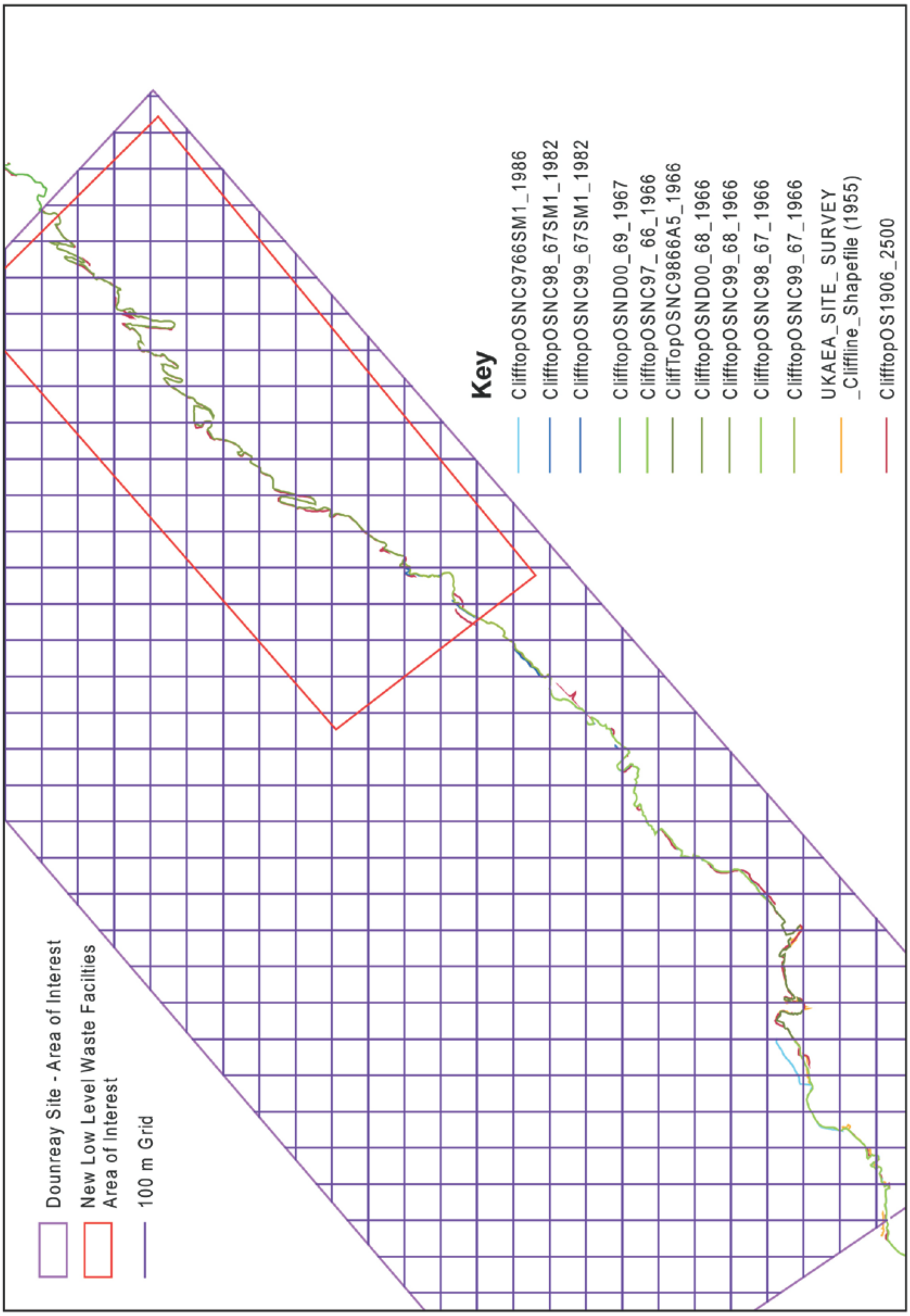


Figure 5. Comparison of cliff top positions digitized from OS topographic surveys between 1906, 1966/67 and 1982/86, and from the Dounreay 1955 site survey.

74 There is generally a close agreement between the 1966/67 OS position and the 1955 survey position within the south western portion of the NLLWF-AOI. Within the portion of the DS-AOI seaward of the DNPE, the 1955 line

commonly occurs between 15 m and 30 m landward of the position digitized from the 1966/67 and 1982/86 OS mapping; a comparable but slightly lower (10-15 m) landward displacement is generally evident when it is compared to the line digitized from the 1906 survey. An exception to this degree of displacement between the 1906 and 1955 cliff top positions is apparent around the south western margin of the NLLWF-AOI, where the digitized 1906 cliff top is slightly more than 30 m seaward of its position digitized from the 1955 survey data.

75 The cliff top between Dounreay Castle and the south western margin of the DS-AOI also shows variable amounts of change relative to its 1955 surveyed position. Seaward migration, in the order of 30-50 m, of the 1966/67 and 1982 cliff lines is evidently associated with tipping of material on to the foreshore adjacent to RN Vulcan. By contrast, all of the cliff line positions north east of Dounreay Castle and those south west of RN Vulcan, show only minor changes, typically in the order of 5 m.

Interpreted_base_of-superficial_deposits

76 Differing styles of hatching were used, in places, on parts of the survey of the cliff line to denote apparent changes in cliff/shore profile. Again, this could only be identified sporadically, notably on survey images covering the south western portion of the NLLWF-AOI and within much the DS-AOI (apart from between Dounreay Castle and the former pumphouse). The digitized line generally separates unornamented ground landward of areas with an ornament indicating exposed bedrock. In most cases, this appears to coincide with the base of the cliff in contact with the rocky foreshore. Since this relationship can only be plotted with any degree of continuity along the cliff within the DS-AOI, where the cliffs appear to have been principally developed in glacial and post glacial superficial deposits, it is interpreted as representing in general terms, the original position of rockhead in the cliff, prior to the development of the DNPE.

Gullies.shp

77 Five examples of narrow gullies cut into the cliff line are clearly identifiable within the ground covered by the Dounreay 1955 site survey. The gully at [^{2}976 ^{9}666] corresponds to the seaward end of a drain that reaches the coast just to the south east of RN Vulcan. A second gully at [^{2}977 ^{9}667] corresponds with drainage of a former pond. It crosses the cliff line in the vicinity of the sluices that drain into Geo Cuinge. The third corresponds with the former position of the mill pond and the Mill Lade burn at [^{2}983 ^{9}669] within the DNPE site area. The gully at [^{2}986 ^{9}673] is now concealed beneath made ground that was associated with buildings c. 70 m east of the former pumping station. The gully at [^{2}992 ^{9}678] is now concealed beneath the made ground of Landfill 42. Few of these gully features are delineated on any of the OS 1: 2,500 scale maps.

78 Close comparison of the gully identified as coinciding with the small drain at [^{2}976 ^{9}666] with the position of the same drain shown on the 1988 and on the 1872/1906 OS maps (and on the 2004 colour aerial photography) shows that the position of the drain has been displaced north eastwards by about 10-12 m on the 1955 Dounreay Site Survey. The feature is coincident on all of these other datasets. This suggests either an inaccuracy in the 1955 surveying or

that an error has occurred in the georectification of the 1995 map tile (georef_ae406548). The latter appears the more likely conclusion, given the difficulties of accurately georeferencing historic paper plans. Other georectification errors may affect the remainder of the 1955 dataset, but nowhere are these as evident as in the displacement of the gully mentioned above. Nevertheless, the possibility that georectification difficulties may account for some of the apparent displacement of the 1955 digitized cliff top position relative to digitized positions form the OS surveys cannot be entirely discounted. The north eastward direction of gully displacement is however oblique to the general trend of the coastline and any seaward displacement is generally in a northerly direction. It appears therefore, that any seaward discrepancy in the position of the 1955 cliff line, relative to its position digitized from the OS mapping, will be relatively minor and unlikely to account for the changes, commonly in the order of more than 30 m, indentified within the DS-AOI.

Coastal Erosion Markers

79 Of the five datasets, that for the coastal erosion markers might be the most pertinent for examining rates of recent cliff line modification. This shows that between 1994 and 1997, 30 sets of markers were sited along (or a few metres seaward or landward) the cliff top, principally within the DS-AOI. Most occur in pairs or triplets, with marker points 5 – 20 m apart. All of the sites were beyond the south western limit of the coastline investigation presented in the Phase 1 report. Consequently, they added little direct evidence of coastal erosion within the NLLWF-AOI. A few however (12A & B; 13A & B; 14A & B), occur just to the south east of that area and lie close to the cliff top positions digitized from all of the vintages of OS 1: 2,500 mapping.

80 Of the 3 sets of markers considered in the Phase 1 study, all but one (14B) occur inland of the cliff line digitized from all of the OS surveys. The site of Marker 14B (Figure 6) now occurs on the foreshore, below the cliff, in the vicinity of [^{2}9913 ^{9}6775]. It now lies immediately seaward of the cliff edge at the southern margin of Landfill 42, and represents a site showing probable minor landward recession of a cliff formed in tipped man-made materials.

Figure 6. Foreshore close to Erosion Maker 14B

81 All of the remaining sets of markers occur along the cliffs between [^{2}990 ^{9}676], close to the north eastern margin of the DNPE, and [^{2}982 ^{9}669] near the north eastern margin of the RN Vulcan site. Although some of the measurements taken by UKAEA in 1997 from these sites (as made available to BGS) appear ambiguous, certain general conclusions can be drawn from the dataset:

- All of the marker pairs (and intermediate readings) were made landward of the cliff edge as digitized from the OS mapping. However, when their positions are plotted in relation to the cliff top digitized using the SocetSet 2004 aerial photography, examination of certain marker pairs suggests that small amounts of cliff top recession have occurred (Figure 7).
- The position of most 'B' markers from the marker pairs of sets 1 to 9, plot seaward of the 2004 SocetSet cliff top; all of the 'A' markers occur either close to the cliff top or landward of it. This is most clearly seen in the most westerly 3 pairs of markers, sited in the vicinity of Dounreay Castle, which might suggest that several metres of cliff top recession has occurred in less than a decade.
- Unfortunately, the data provided by DSRL gives all of the marker locations as 'approximate' and therefore their true positions cannot be verified. Consequently there are very accurate dGPS positions of 'approximate' locations. This is borne out by the discrepancy observed between the separation of 'A' and 'B' markers, as plotted on the GIS from the dGPS co-ordinates supplied and the separations recorded by field measurements conducted with a measuring tape in 1997. For example, the separation recorded between 'A' and 'B' markers at Station 9 in 1997 was 11.76 m, whereas the separation of the plotted locations on the GIS is 18.3 m.

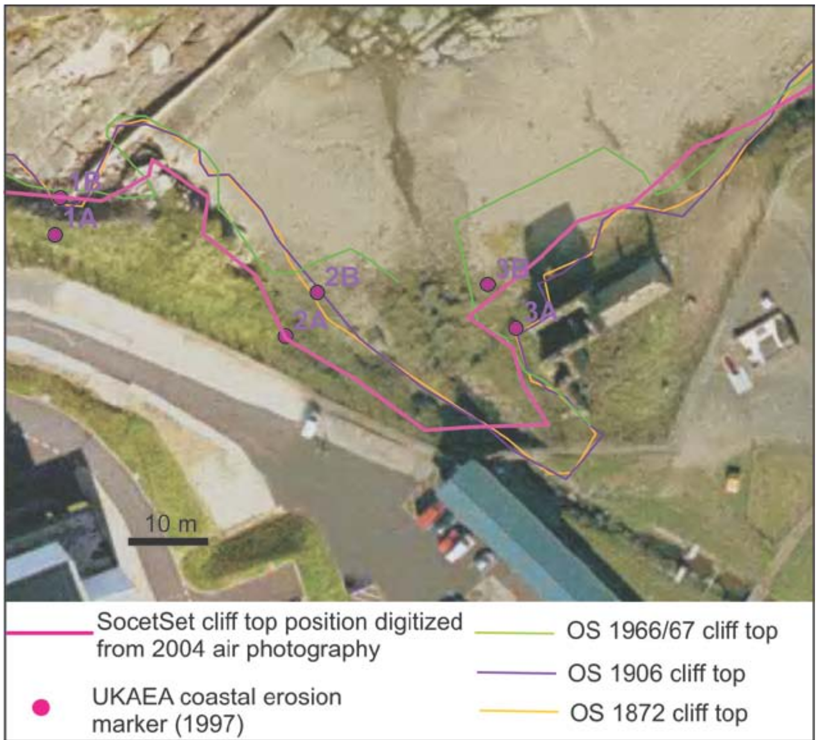


Figure 7. Plotted locations of Erosion Markers near Dounreay Castle in relation to digitized cliff top positions.

82 These uncertainties severely limit any conclusions that can be drawn from the Erosion Markers dataset concerning the recent rates of cliff recession within the DS-AOI.

83 Intermediate elevation measurements were taken at two of the marker sites (Marker Stations 1 and 5) that were established in 1994, in order to establish the nature and amount of any changes to the cliff profile at these locations. Figure 8 shows the measured changes in profile at Marker Station 5, between April 1995 and January 1997. The plot, which was supplied by DSRL, shows a minor amount of seaward advance and increase in elevation of the profile during the 21 month interval between measurements. It also shows a slight shallowing of the facet of the profile seaward of the second (from the landward end of the profile) intermediate measurement point. This profile appears to indicate active cliff advance over a relatively small time interval, but perhaps more importantly, it illustrates the nature of the cliff profile and the difficulty in establishing an unambiguous 'cliff top' position which can be confidently established along the cliff line, either by remote sensing or even by direct measurement. This is a particularly important limiting factor when attempting to compare relative rates of change across both of the areas of interest. This topic is discussed further in paragraphs 89-90 below (see also Figure 9).

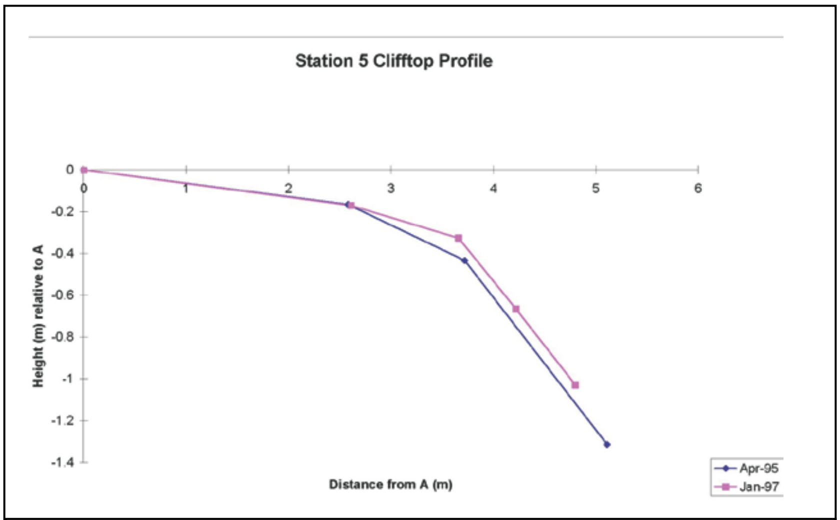


Figure 8. Measured changes in cliff profile at Erosion Marker Station 5 between April 1995 and January 1997.

The Differential GPS Survey June 2008

Field data

84 One hundred and nine points (at c. 20 m intervals) were surveyed along the cliff top covering the ground within the NLLWF-AOI, between the north eastern margin of the Dounreay Site [^{2}99274 ^{9}67910] and [^{3}00333 ^{9}68980], north west of Glupein na Drochaide. The survey was conducted by BGS on 11 June 2008

using the DSRL Land Remediation Department Trimble 5800 RTK dGPS system which provides centimetre resolution, real-time positioning in 3D. The system utilises a radio signal from the Nuvia base station in building D9807 on the DNPE site, to provide the real-time correction to the rover's position.

85 The receiving antenna was placed as close as possible to the cliff edge (usually to within 1m) although safety considerations meant that in a few instances the point reading was made a few metres landward of the edge. This was converted into the Arc Point .shp file **CLIFF_POINTSJune08_3D.shp** included within the project GIS.

86 A profile of the cliff top was constructed joining the surveyed points by straight lines using the Advanced Editing Tool in the Arc9.2 Editing Suite. This produced **DGPS_CLIFFJune08.shp**, (as an Arc Polyline .shp file). A smoothed profile **SMOOTH_CLIFF_POSITIONJune08.shp** was produced by initially converting the GPS point locations along the cliff into a polyline. This line was then smoothed using a T-Spline function contained within the ArcGIS add-on ET Geowizards. This ensured the exact location of the original coordinates were preserved.

87 The accuracy of the cliff line profile can be gauged, in the south western portion of the survey area, by comparing it to the distribution of data points collected by the DSRL Offsite topographic survey conducted in 2000. All of the Off Site survey data points lie landward of the Point and Polyline .shp files generated from the 2008 dGPS cliff top survey.

Limitations of the dGPS survey

88 Although dGPS surveying is extremely accurate, there are several factors limiting its effectiveness in truly representing a position of the 'cliff top' as depicted on the OS maps. Most relate to safety considerations, which would have also have impacted on the accuracy of any ground surveying involved in the production of the OS maps:

1. Survey points were restricted to locations where the ground was seen to be safe to walk on (for example, areas of slippery ground and ground strewn with loose or unstable boulders and gravel were avoided).
2. Surveying was not conducted on rock promontories where access was unsafe. These included ground where climbing would have been required for access, or where long narrow blow holes (too small and too narrow to be depicted on even the largest scale OS maps) separate the promontory from the main cliff line.

89 In some instances, another major limitation was the difficulty in deciding the exact position of the 'cliff top' (see Figure 9). Where the cliff profile is steep, or near vertical, with a pronounced break of slope (Figure 9A) the position is clear and it is easy to locate and survey. Where the cliff profile is rounded, with many small breaks of slope (Figure 9B), the cliff top position is uncertain and difficult to record consistently. In Figure 9B the position could be taken as close to the red figure, or the green figure (or at any position between the two).

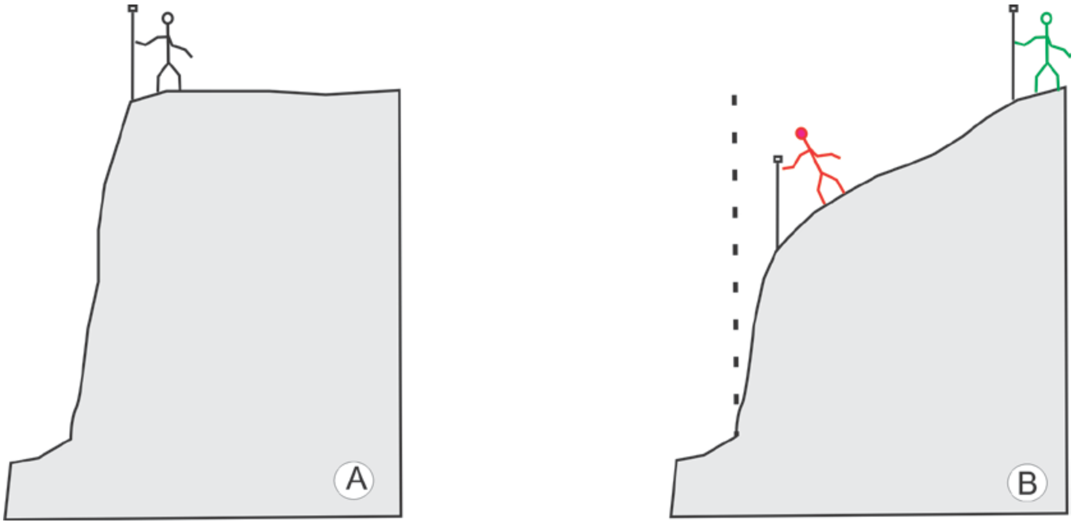


Figure 9. Determining the cliff top position by dGPS measurements; A ~ near vertical cliff profile, B ~ rounded cliff profile. Dashed line ~ possible cliff top/cliff edge from OS map.

Comparison between dGPS and Arc digitized cliff top positions from the OS maps

90 As the 2008 dGPS survey line only extends north eastwards along the coast from the north eastern margin of the Dounreay Site, comparing the current position of the cliff top as recorded by that survey, and its indicated former positions digitized from the OS 1: 2,500 surveys, is only possible between [^{2}99274 ^{9}67910] and [^{3}00333 ^{9}68980]. For much of its length, from [^{2}99300 ^{9}67998] to its NE limit [^{3}00333 ^{9}68980], no 1982 1: 2,500 scale survey data were available; in this area, comparison of the cliff top position can only be made with the lines digitized from the 1966/67, 1872 and 1906 OS surveys.

1872/1906 surveys

91 As previously noted, the digitized positions of the cliff top on the 1872 and 1906 maps are almost coincident and, in general, show a close agreement with the position of the cliff top derived from the 2008 dGPS survey. Along much of the dGPS line the surveyed points occur within 4–5m distance of the 1872/1906 line. Most lie landward of the 1872/1906 cliff top line, but a significant number (c 25%) occur seaward of it. This again indicates the difficulties in comparing datasets derived by different methods but also highlights possible inaccuracies in the surveying and inconsistencies in graphic representation of the cliff top on the early OS maps.

92 Bearing these limitations in mind, however, it is clear that from c. 90 m north east of Oigin's Geo [^{2}99578 ^{9}68402] to [^{2}99932 ^{9}688715] c. 30 m east of Geodh nam Fitheach (along c. 440 m of the coast), the digitized positions of the 1872/1906 cliff top occur a significant distance (typically 20–30 m) seaward of the dGPS position. At first sight therefore, this appears to be a stretch of the cliff line which may have undergone significant retreat in the last 100 years. However, it is probable that several of the limitations on the dGPS data for accurately depicting the cliff top position, outlined above, apply in this area, notably a rounded cliff profile and access impediments to the true seaward edge of the cliffs. Nevertheless, the difference between position of

the cliff edge, recorded during the dGPS survey and its position on the 1872/1906 topographic maps, identified the Oigin’s Geo - Geodh nam Fitheach area as a target for more detailed photogrammetric investigation (see below).

93 A similar, but much smaller area of possible cliff top recession is indicated when comparing the 1872/1906 cliff top and the 2008 dGPS data for the coast in the vicinity of Glupein na Drochaide [^{3}00190 ^{9}68905] at the north eastern end of the NLLWF-AOI. Here the 1872/1906 cliff top positions on two small promontories and an intervening geo vary a small amount (local discrepancies in the order of 10–30 m) from their positions indicated by the dGPS points. In some places, the dGPS cliff top line lies seaward of the OS cliff line, but in others it occurs landward of the OS position; a combination of access difficulties for the dGPS, and surveying inaccuracies for the OS data, may account for many of these differences. This was also identified as a target for further investigation using the time series of aerial photography (see below).

1966/67 surveys

94 A pattern of off-sets, similar to that seen in the 1872/1906 data, is evident between the line digitized for the position of the cliff top from the 1966/67 OS data and dGPS survey. Again, there is close agreement between the datasets along most of the area examined, suggesting only minor cliff recession across much of the AOI. Discrepancies occur along the same portions of the coast (between Oigin’s Geo and Geodh nam Fitheach and around Glupein na Drochaide). However, there is near coincidence between the 1872/1906 and the 1966/67 OS cliff top positions in >90% of both areas. This lends weight to interpretation of the apparent changes as largely resulting from cartographic changes between the different vintages of map and probable surveying access difficulties.

95 An exception to the correspondence between the 1872/1906 and 1966/67 cliff top lines, is the cliff position at the head (landward end) of the geo at [^{3}00146 ^{9}68889] immediately west of Geodh nam Fitheach. Here the digitized position of the 1966/67 cliff line closely agrees with its position from the 2008 dGPS; the 1872/1906 position is some 27 m further landward. This again suggests variability in the depiction of the cliff top between the different vintages of OS survey, rather than true large-scale coastal modification.

7 WALK-OVER RECONNASSANCE OF THE DS-AOI FORESHORE

96 A walk-over reconnaissance of the near shore area of the DS-AOI was conducted on 21 September 2009, with the aim of examining the nature of the materials that make up the present day cliffs. It also produced an accurately located record of a representative selection of localities that span the coast between the south western margin of the NLLWF-AOI and Geo Cuinge. The walk-over was conducted by C A Auton, accompanied by G Morgan of DSRL.

97 A south westerly traverse was undertaken along the coastline and a total of 20 Field Observation Points [FOP's] (CAA _1 - _26) were briefly examined and digitally photographed using a camera supplied by DSRL. The position of each locality was captured within a bespoke GIS project using a ruggedized Tablet PC (Xplore iX104C3V) which has an integrated GPS, and an outdoor-readable screen, with a touch screen facility via a stylus/pen device. This equipment uses BGS SIGMA *mobile* (System for Integrated Geoscience Mapping) software, developed by BGS. This enables georectified vector data to be captured and displayed with raster data (such as digital maps and aerial photographs). The Tablet PC runs Microsoft XP for Tablet software, while the map interface uses a customised version of ESRI ArcMap and a linked MS Access data base.

98 No records were collected for 6 FOP's allocated in the data base: CAA_3, _12, _13, _15, _23 and _25.

99 All of the FOP's for which records were made are included within the project GIS as a point Shape file, **Images_Dounreay2009.shp,** that is included in the **PHOTOGRAPHS** folder. This folder also contains all of the digital photographs.

100 All of the SIGMA *mobile* data from the reconnaissance is presented in Appendix A. This was produced from an automatic report generation tool in the SIGMA *mobile* Field Report System. This tool interrogates the underlying Field Notebook tables in the SIGMA system, for data, and builds a real-time structured Microsoft Word 2007 document. To achieve this, it runs a complex set of pre-determined Structured Query Language (SQL) queries which group all of the data recorded at each individual Locality Point. This results in a fully self-contained dataset, linking field descriptions and photographic images.

Hyperlinking photographs and Locality Points in the GIS Project

101 The digital photographs taken during the reconnaissance survey can also be viewed directly, by hyperlink, from within the GIS. The hyperlinked Photography layer was created by joining relevant FOP/Locality Point data, all related photographic images and all of their attributes, and exporting them into a single table for integration with the GIS system. This table includes NGR values which were then imported into the GIS and subsequently converted into the Images_Dounreay2009.shp shapefile. A column called 'Link' was added to its attribute table in the GIS and the PHOTOGRAPHS folder's location was hardcoded into this column. The shapefile was then activated in Layer Properties under the Display Tab to support hyperlinks in the GIS.

Viewing hyperlinked photographs in the GIS

1. Select Images_Dounreay2009.shp in the Table of Contents (TOC) in the .mxd
2. Select the lightning bolt from the Tools Toolbar.
3. Hover over the 'Locality Point' on the map face until the path name of the photograph appears. Then left click the mouse.
4. The photographs for each Locality Point will appear in the computer's default picture viewer, such as Windows Picture and Fax Viewer.

102 Problems may occur if the default picture viewer is a non-standard type (such as Picasa). In this case, the default picture viewer will need to be changed using the Windows Control Panel.

103 It may also be necessary to change the hardcoding of the location of the photographs in the 'Link' column of Images_Dounreay2009.shp, to match the storage location of the images once they are loaded from the CD accompanying this into a new computer. To do this: Open the Attribute Table; Activate the Editor Toolbar – Editor – Start Editing the 'Link' column in the Attribute Table to match the location of the PHOTOGRAPHS folder; Save Edits - Stop Editing.

104 To change the 'Link' to be a 'relative' link, place **..** before the start of the PHOTOGRAPHS Folder. For example:

105 ..\PHOTOGRAPHS\CAA_1_21092009_01.JPG

106 Relative linking enables the location of the PHOTOGRAPHS folder to changed to suit the user's computer set-up, rather than requiring it to be located on the PC's hard drive (usually the 'C' drive on most machines).This allows the computer to search directly for the folder wherever it is located.

Results of the Walk-over Reconnaissance

107 The walk over commenced on the foreshore adjacent to the north eastern fence of the DNPE site. Here the made ground of Landfill 42 was seen to rest on a gently eastwardly sloping flagstone surface. The flagstone forms a steep cliff, 7 – 8 m-high, immediately seaward of the first locality (Appendix A ~ FOP CAA_1). This lies close to the cliff top position digitized from all of the OS 1: 2,500 scale surveys, but is some 50 m seaward of the cliff edge shown on the 1955 Dounreay site survey. The 1955 cliff is concealed beneath the made ground.

108 The exposed trace of the Dog Track Fault was viewed from FOP CAA_2, which shows it to occur on at the head of a v-shaped geo that widens in a north-north westward direction. The geo is mainly floored by a thin spread of cobbly beach gravel resting directly on flagstone.

109 The shatter-zone of the Dog Track Fault was examined at FOP's CAA_4 and _5 where it was seen to be 4 m-wide. The shatter-zone contains a fault breccia of angular cobbles of flagstone which is cemented, in places, by calcium carbonate, on its north eastern side. The cemented material, which is up to 1 m thick, is clearly more resistant to erosion than the clay-bound cobbly and bouldery fault gouge, which extends along the south western side of the fault. The clay-bound material floors a linear notch some 20 cm lower than the

cemented breccia and the adjacent flagstone, on the eastern side of the geo and some 2.5 m lower than flagstone surface on the headwall side of the fault.

110 The clayey fault gouge was best exposed close to the head of the geo and was seen to disappear beneath made ground forming the cliff top. Erosion appears to have been enhanced along the zone of shattering associated with the Dog Track Fault but, apart from some minor changes to the cliff line at the head of the geo, the topographic form of the feature appears little altered on all of the vintages of OS 1: 2,500 scale maps. The present cliff top position at the head of the geo lies a few metres seaward of its position shown on the 1955 Dounreay site survey and it appears that changes in its position since the initial 1872/1906 OS surveys have been in the order of a few metres and a result of the interplay between erosion and tipping of material beyond the 1955 cliff edge. A modern minor landward recession of the cliff was indicated by the set of erosion makers (14 A and B) at the head of the geo (see paragraph 81 above). Cliff recession may also be suggested by the NGR plotted for FOP CAA_5 (within the geo). This lies landward of the cliff edge plotted from the 1872/1906, 1966/67 and 1982/86 OS survey data. This surmise should be treated with caution however, because of the limited accuracy (typically ± 20 m) of the GPS readings available from the GPS integrated within the Xplore Tablet PC used during the walkover survey.

111 The present cliff top is developed in made ground at all of the FOP's between [^{2}990 ^{9}676] and [^{2}985 ^{9}672] (CAA_6 – _17) which are located along c.450 m of the cliff line seaward of the main part of the DNPE site. The lower parts of the cliff profile are developed in shallow dipping flagstone bedrock at CAA_6 (Figure 10) but the man-made material extends to the base of the cliff between CAA_7, _8 and _9.

Figure 10. Cliff line at CAA_6 and _7 developed in made ground. Note blocks of concrete and orange sandstone, washed from of tipped material, lying on flagstone platform.

112 Evidence of active erosion of the present cliff line is widespread, with blocks and boulders of concrete and sandstone spread across the flagstone shore platforms. All of the profiles developed in the unconsolidated materials are steeper than those which would form at the normal angle of repose of the material, and most are unvegetated. These attributes suggest an unstable cliff line, subjected to erosion by waves or sea-spray during storms. The most active erosion appears to have occurred around FOP's CAA_8, _9 and _10, where the man-made deposits reach to the base of the cliff. This has produced a characteristic convex profile in the lower part of the cliff, with a notch developed at its base. Large blocks of rock have been placed seaward of the cliff in an attempt to slow the rate of cliff retreat (Figure 11; see also FOP CAA_11, Appendix A). The speed of this erosion can be inferred from a written comment received from D Graham 9 (DSRL), received by BGS on 25th June 2010, on the first draft of this report. He reported that 'in the late 80's' there were 'some man-made deposits, including re-bar like items, sticking out of the deposits' on the top of the stack at [298910 9675533] shown in Figure 11.

113 Graham's comment is important, as it is clear observational evidence that made ground extended tens of metres beyond the present cliff line in the vicinity of FOP CAA_8, and indicates that it has been removed since the 'late 1980's'. The location of the stack precluded detailed examination of the capping deposits during the reconnaissance survey, but there appeared to be no trace of man made materials on the stack at the time of the walk over survey, perhaps indicating that they have fallen onto the foreshore platform since Graham's observations were made. This topic is considered further in the photogrametric study of rock reefs and stacks in paragraphs 181 and 182.

Figure 11. Convex profile in lower part of cliff in man-made deposits at CAA 8. Note: stack capped by a mixture of *in situ* Quaternary deposits and made ground.

114 Several other attributes of this part of shoreline seaward of the DNPE site became evident during the reconnaissance:

1. The area has been a site of active coastal erosion for many years as indicated by the development of sea stacks and natural arches (see Appendix A, FOP CAA_9). The stack at FOP CAA_9 has a capping of vegetated *in situ* Quaternary sediment (close examination was impossible, but the material resembles solifluction deposits developed on glacigenic till that are common elsewhere in the Dounreay area). This remnant of undisturbed Quaternary material indicates that the original cliff line within the DNPR site area is likely to have been primarily cut into flagstone bedrock and to have been capped by a thin cover of Quaternary sediment.
2. The cliff line position is more stable when the lower portion of the cliff face is developed in bedrock. This enables vegetation cover of older slopes developed in unconsolidated deposits. A cursory examination of many of the cliff faces (such as those at FOP CAA_14 and CAA_17) might suggest that *in situ* glacial till occurs beneath the obvious deposit of bouldery and cobbly made ground seaward of the DNPE site. Closer examination of the ‘till-like’ material however, shows the deposit to have several attributes that differ from undoubted *in situ* tills in the surrounding Dounreay area. These differences include its colour (it is typically pale to moderate brown, whereas most *in situ* tills are reddish brown or olive grey), and its clast composition and grain size (it is typically more sandy and bouldery, and contains a mixture of large blocks of sandstone and flaggy siltstone, as well as sparse igneous and metamorphic rocks). Nearby *in situ* tills normally contain a predominance of clasts of either sedimentary rocks, or a mixture of igneous and metamorphic clasts; they seldom contain a mixture of boulders of all three types.
3. In some instances, the till-like sediment possesses steeply inclined well developed stratification that dips shoreward (see Figure 12). Stratification is generally only weakly developed in *in situ* tills exposed in the Dounreay area and, where present, it is normally sub-horizontal. These ‘till-like’ deposits seaward of the DNPE are also much less consolidated than unaltered tills in the surrounding area; the former can be readily dug with a spade or trowel, the latter commonly require a pick axe.
4. The properties of the ‘till-like’ deposit outlined above are well illustrated at FOP CAA_17, where it is a bouldery, pale brown, sandy diamictic deposit, which rests directly on flat lying flagstone bedrock. Close examination of the base of the face shows bricks, rusting metal debris and a pod of disturbed gravel within the deposit less than 1 m above the bedrock contact. These types of man-made debris are also present in several other exposures and support the conclusion that this ‘till-like’ material is in fact made ground, bulldozed into its present location during the early phases of construction on the DNPE site.

Figure 12. Field Observation Point CAA 17, showing steeply inclined stratification dipping onshore. Inset shows included brick debris and pod of disturbed gravel (see compass for scale).

115 Man-made modifications to the cliff line and foreshore are even more evident at FOP's CAA_18 and _19. The former shows sea defences made up of large blocks (up to 3 m diameter) of Reay Diorite emplaced behind a concrete retaining wall associated with the former pump-house and jetty complex north of the Dounreay reactor dome; the latter is the Shaft Isolation Project Raised Working Platform, which extends tens of metres seaward across the foreshore. Both features protect a significant proportion of the cliff line from marine erosion.

116 Field Observation Point CAA_20 provides a panoramic view of the foreshore near Dounreay Castle. Here, a small sandy beach is developed on the flagstone shore platform, which is backed by a low cliff capped by blown sand. This is the only portion of the foreshore within the DS-AOI that shows little modification by man, apart from the numerous concrete jetties that extend into the sea across the flagstone wave-cut platform.

117 The jetties that extend seawards around Scarbach Geo are clearly seen from FOP CAA_21, where a low cliff mantled in made ground backs the flagstone wave-cut platform. The cliff line then rises gradually in elevation south westwards, to reach a height of some 7 m above the platform as the made ground that protects the RN Vulcan site becomes thicker. Rectangular concrete blocks, up to 5 m in circumference, mantle the shoreward edge of the wave-cut bedrock platform. They are particularly abundant around the outfall at FOP CAA_22 (see Appendix A). Again, there is little evidence of *in situ* Quaternary sediment occurring between the made ground and rockhead, suggesting that the cliff line is developed in materials that have been bulldozed into place. This view is supported by the relative positions of cliff line digitized

from the 1955 site survey and those recognised from the 1966/67 and 1982/86 OS surveys (see paragraph 75 above).

118 The configuration of the made ground seaward of RN Vulcan is evident from FOP CAA_24, which shows a grass-covered cliff top rising 2-3 m above the level of a gently inclined ramp of flagstone bedrock. The ramp passes seaward into a broad wave-cut platform of flat lying flagstone.

119 The almost horizontal bedding of the flagstone sequence is also evident at the final locality visited, Geo Cuinge (FOP CAA_26). Here, an outfall enters the sea at the north western corner of the RN Vulcan site. The present day rectilinear form of the geo might suggest that it's shape has been significantly altered by man, but the trend and width of the feature appear little altered from that shown on the 1872/1906 OS maps. Apart from the concrete jetty that crosses the geo at its seaward end, there is little direct evidence of human influence on its form. Its depth and the almost parallel form of its sheer sides may suggest that it was quarried at one time, but compelling evidence is lacking. The feature trends NW–SE, which is indeed unusual, as most other geos in the area trend SW–NE or SSE–NNW. Its trend however, follows that of the widely-spaced, rectilinear, dominant, near-vertical joints in the surrounding flagstones.

120 Human modification of Geo Cuinge is evident at its landward end, where construction of the outfall has altered the width and orientation of a pre-existing gully that was recorded on the 1955 Dounreay Site Survey.

2 PRODUCTION OF GEORECTIFIED STEREOSCOPIC AERIAL PHOTOGRAPHIC IMAGES

Phase 1 study photogrammetry

121 Seven sets of aerial photographs of different historical vintages from 1946 to 1988 (Table 2), were examined and photogrammetrically scanned from negatives at the Royal Commission for the Ancient and Historical Monuments of Scotland (RCAHMS) during the first phase of this study. This first phase work concentrated only on the photography covering the NLLWF-AOI. Unfortunately, no camera calibration certificates were held by RCAHMS, nor by any of the originators of the images (Ordnance Survey, RAF, Blom Aerofilms for Clyde Surveys), rendering the process of orthorectification of the images extremely complicated. Camera calibration enables exterior orientations of images to be calculated rapidly; without this calibration, a complex warping model for the camera lens needs to be generated, using known control points. This resulted in very lengthy processing times, as metadata (other than the vintage of the photography) were missing.

122 Because data regarding altitude, camera focal length etc. of each set of photographs, which is crucial to their efficient georectification, was absent the construction of digital stereoscopic models and their incorporation in bespoke Arc9 compatible SocetSet© software took many weeks for each set of photographs.

123 The SocetSet© application performs functions related to photogrammetry. The software constructs stereoscopic (binocular) images from paired georectified digital aerial photographs, or from digital photogrammetric scans of analogue photography. When linked to an ArcMap© project SocetSet enables digitization of topographic features, using standard Arc capture and editing tools, as georeferenced vector data (polylines or polygons). These can be placed in 3D space, if the imagery is draped over a suitable Digital Elevation Model (DEM) that can be incorporated within the SocetSet application. Tiled orthorectified (true-scale) images of the photography (Orthophotos) were used for illustrating the landscape and as a backdrop for plotting the vector data in 2D. for the analogue photography of the Phase 1 study they were constructed using DEM's derived from the digital photogrammetric scans (see below).

124 After extensive enquiries, limited camera calibration data were obtained for the most recent (1988) analogue photography that was available during this phase of work. This enabled the eventual construction of a stereographic model for this data and its incorporation into SocetSet for digitising. The process involved calculating the exterior orientations of the images using ImageStation, and interior orientations using selected ground control points held within the project GIS (1: 2,500 scale OS maps, Dounreay site dGPS On Site and Off Site survey points). A DEM was created using these orientations for the 1988 RCAHMS imagery, from which DEMs were derived for the remaining sets of images. This involved many man-days of effort for each vintage of photography. Consequently, although seven vintages of georectified aerial photographs were available, only four were evaluated (1943, 1951, 1965 and 1988) in the phase 1 study; of these the 1951, 1965, and 1988 images were output into SocetSet format, with full orthorectification and DEM ground

control. This enabled generation of line work along the cliff edge represented in images of the three vintages, covering a time span of 37 years.

125 Despite the difficulties described above, the georectification accuracy obtained for the Phase 1 stereoscopic models generated for the aerial photographic datasets, although variable, exceeded that obtained from the OS topographic datasets (typically ± 5 m). Accuracy of the X–Y positions on the stereoscopic models was typically in the range of c. 1.4 m to < 2.2 m with the most accurately modelled X–Y positions, for the 1965 dataset, being c. 83 cm. This high level of accuracy (which was increased further during Phase 2 of this study; see Phase 2 photogrammetry below) lends a significant amount of confidence in the validity of the cliff top positions interpreted from the SocetSet stereoscopic views.

126 The scanned 1943 photography (italics in Table 2) was examined, but the quality of the photogrammetric scans was such that it was regarded as impractical to attempt the huge amount of further processing required to produce adequate georectified ortho and stereographic models necessary for import into SocetSet. This is a pre-requisite for accurate digitisation of the cliff top position. This problem is largely a consequence of the orientation of the flight-lines for the photography, which cross the coast at an acute angle, leading to irregular and unusually shaped photogrammetric scans. These would have resulted in varying amounts and orientations of stereoscopic overlap along the coast, which would have been extremely difficult to rationalise.

Phase 2 study photogrammetry

127 The successful construction and interpretation of georectified stereoscopic models derived from the historic aerial photography in the first phase of the study is described further in detail in Auton *et al*. (2009) [3]. This led to the methodology being extended to the interpretation of similar models covering the DE_AOI during the second phase of study. The results of both phases of work are described below.

128 The methodology was refined during the second phase study in order to address some of the problems of georectification encountered during the earlier work. Although no further camera calibration data were available that could be applied to the historic photography, 3D georectification was enhanced by the collection of new dGPS data for specific sites that are present in the landscape today (such as the junctions of field boundary walls, ends of walls, gateways etc.) and which were present and visible on the historic photographs. The dGPS co-ordinates were collected by DSRL staff, for a spread of sites, selected by BGS, across the hinterland of both Areas of Interest.

129 The resultant dataset has been included in the project GIS as a 3D shape file, **new_GPS_gcps_3D_heights.shp**. The new dGPS sites are concentrated at the south western and north eastern edges of the Areas of Interest, beyond the ground covered by the pre-existing UKAEA ‘Site’ (1996) and ‘Off Site’ (2000) topographic surveys. The shape file is labelled within the GIS (and each point displays within the .mxd) with 3 attributes: the Point Identification (PID) number is shown in black; the elevation (in metres above OD) is shown in blue and a brief description of the location is shown in brown.

130 Additional imagery from the three (1951, 1965 and 1988) datasets of historic monochrome photography that were examined was photogrammetrically scanned, to extend coverage across the DS-AOI and to fill-in gaps in the Phase 1 study. Topographic corrections were made to the constructed DEM's and new and improved stereoscopic models were made for each vintage of photography. The improvement in accuracy of modelled positions, which was typically in the range of c. 1.4 m to < 2.2 m in the Phase 1 study, was improved to lying within a range of c. 0.6 m to < 1.8 m for the modelled X–Y positions of the 1988 and 1965 datasets; improvement of the 1951 imagery was more sporadic. Only two stereo model pairs were constructed from these latter images during the Phase 1 study (see Table 3 of Auton *et al*., 2009) [3]. These had modelled X–Y positions in the range of c. 1.8 m to < 2.2 m. For seven of the seventeen 1951 stereo pairs constructed in Phase 2, accuracy of modelled X–Y values was better than 1.5 m (see Table 3); in the worst case (Model: 3060+3061), however, the variability exceeded 6.8 m. Nevertheless, the overall improvements to the already generally high level of accuracy of the models increases the confidence that can be placed in the validity of most of the interpreted SocetSet cliff top positions.

131 As a result, the 1965 and 1988 datasets now correlate well with each other and with the 2004 digital imagery. However, the relative inaccuracy of the 1951 images is also evident. The latter have non-linear distortions, which can be seen from the displaced locations of the dGPS points when observed in the correct positions (e.g. at fence intersections) in the 1951 imagery. They appear to be in the wrong positions on the image, because no lens distortion information was available for the 1951 photography. Very accurate individual camera calibrations were constructed for each 1951 photograph, but only for the positions of the four fiducial marks (the very short lines located in the top, bottom, left and right edges of each image). Also a nominal focal length of 508 mm had to be assumed for the lens of the camera used in the 1951 photography.

132 The limitations of the 1951 imagery mean that the digitized cliff positions will be considerably less accurate than those digitized from the later datasets. However, it was noted during the Phase 1 study that, within the limited area digitized, the 1951 SocetSet cliff top position was in close agreement with the cliff edge position shown on the 1955 Dounreay Site Survey. This close agreement was also evident in the much larger area digitized during the Phase 2 study (see below). This indicates that the cliff line derived from the SocetSet model of the 1951 imagery is probably an adequate interpretation of its position at that time.

133 Final orientation results for all of the new 1951, 1965 and 1988 stereoscopic models are given in Table 3. It should be noted that two of the 1951 models have no values for height (Z) accuracy, because it was not possible to obtain sufficient numbers of accurate height measurements for these particular models to produce a realistic estimate.

134 Digital colour stereoscopic vertical aerial photography for the Dounreay area was not available at the beginning of the Phase 1 study, but fully orthorectified, modern digital colour imagery (flown in 2004) became available during 2009 (as 1 km^2 tiles from Getmapping plc). This was purchased, and placed into SocetSet and digitized in a matter of hours, during the second phase of study.

It is, to date, by far the most accurate and informative imagery of the coast in the Dounreay area. Georectified monoscopic digital colour images were also purchased as part of the Getmapping dataset; these were tiled to produce a coloured orthophoto covering both AOI's.

Limitations on interpretation and digitisation of the aerial photography datasets

135 There are many constraints on the conclusions that can be drawn from the digital interpretation of the historic air photo datasets for the Dounreay site area. Chief amongst them are the lack of adequate metadata for each, alluded to above, and the consequent difficulties of placing the stereographic images accurately in 3D space. Once these difficulties were overcome however, the resolution of the morphology of the coastline is excellent. To date, the clearest, most accurate images have been produced from the 2004 digital colour photography (see Figures 13 and 14).

136 Because each set of aerial photographs was taken at unspecified times, relative to low and high tide, there has been no attempt to digitise high and low water mark, and no objective comparison can be made between the breaker zone on the shore and MHWS or MLWS OS data. This also limits interpretations that can be made to changes in the size, extent and form of rock reefs and sea stacks on the foreshore over time (see paragraphs 178 -180 below).

137 It is also evident that the cliff top position on the air photographs generally occurs landward of the position of the cliff interpreted from OS data of comparable vintage. This may be due, in part, to georectification differences between the datasets, but it also appears to be largely because the cliff edge/cliff top interpreted from the OS maps is lower down the cliff profile (see Figure 9B). This is most evident seaward of the DNPE, where the cliffs are cut partly in unconsolidated materials and their profiles range from near vertical to < 60°. Here, the cliff tops digitized from the 1965 and 1955 aerial photography commonly occur several metres inland of their bases on the comparable 1966/67 OS dataset. It is generally much less evident within the NLLWF-AOI, where most of the cliff profile is very steep or vertical and cut in bedrock.

138 It is also noteworthy that a survey was conducted during 1997 that produced a series of stereoscopic oblique views of the coastline (Fisher, 1998) [6], but these could not be used to generate stereoscopic models, suitable for importing into SocetSet, as no camera calibration or accurate positional data were retained from this survey to enable accurate placement of the imagery in 3D space. This is a pre-requisite for accurate digitisation of the cliff top position.

Dounreay 1988 model data				
Model: 226 + 227 RMS Control	X (m)	Y (m)	Z (m)	XY (m)
	1.725	1.683	0.127	1.704
Model: 227 + 228 RMS Control	1.289	1.428	0.693	1.360
Model: 228 + 229 RMS Control	0.682	0.572	0.270	0.630
Dounreay 1965 model data				
Model: 15 + 16 RMS Control	0.788	0.727	0.404	0.758
Model: 16 + 17 RMS Control	0.635	0.782	0.341	0.712
Model: 17 + 18 RMS Control	0.804	0.924	0.186	0.866
Model: 18 + 19 RMS Control	0.909	0.873	0.241	0.891
Model: 19 + 20 RMS Control	0.669	0.845	0.366	0.762
Model: 20 + 21 RMS Control	0.775	0.817	0.268	0.796
Model: 21 + 22 RMS Control	0.640	0.895	0.293	0.778
Dounreay 1951 model data				
Model:3049+ 3048 RMS Control	1.156	1.154	0.562	1.347
Model:3048+ 3047 RMS Control	1.066	1.309	0.725	1.194
Model:3047+ 3046 RMS Control	1.584	1.361	0.706	1.476
Model:3056+ 3057 RMS Control	0.852	1.747	~	1.374
Model:3057+ 3058 RMS Control	0.656	1.548	~	1.189
Model:3058+ 3059 RMS Control	1.367	2.557	1.191	2.050
Model:3059+ 3060 RMS Control	2.658	0.876	0.002	1.979
Model:3060+ 3061 RMS Control	8.484	4.602	0.317	6.825
Model:3061+ 3062 RMS Control	0.570	2.056	1.205	1.509
Model:3062+ 3063 RMS Control	0.978	2.104	2.777	1.641
Model:3063+ 3064 RMS Control	2.081	2.519	1.859	2.310
Model:3064+3065 RMS Control	1.590	2.143	2.226	1.887
Model:3065+ 3066 RMS Control	2.773	2.793	2.898	2.783
Model:3066+ 3067 RMS Control	2.467	2.839	2.570	2.660
Model:3067+ 3068 RMS Control	1.773	1.925	2.847	1.850
Model:4056+ 4057 RMS Control	1.362	2.391	0.636	1.945
Model:4057+ 4058 RMS Control	1.611	1.168	1.079	1.407
Model:4058+ 4059 RMS Control	0.698	1.362	0.724	1.082

Table 3. Accuracy of the aerial photography stereoscopic models

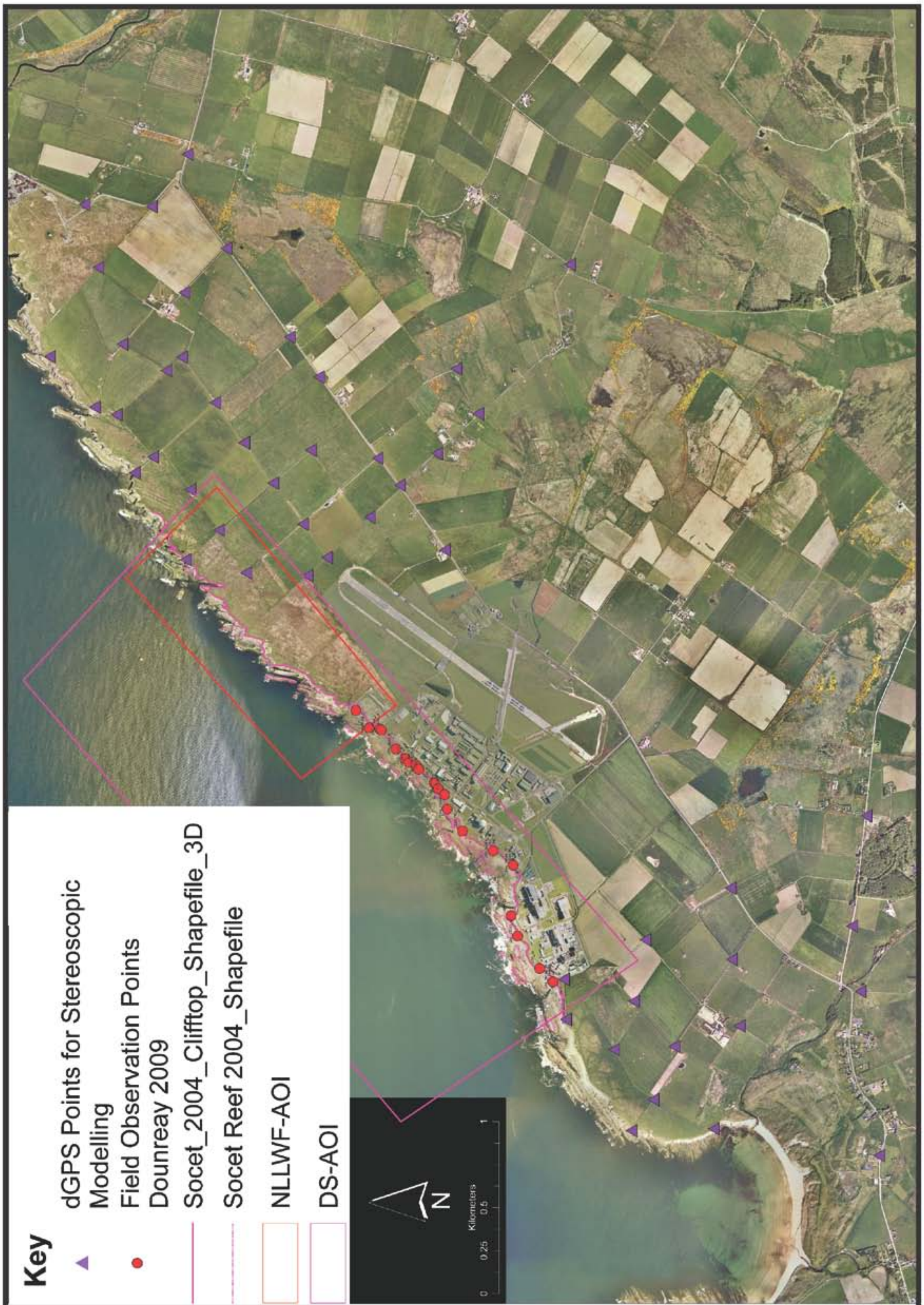


Figure 13. Orthorectified digital colour aerial photography of the Dounreay area in 2004. This shows SocetSet interpretations of cliff top and rock reef positions in 2004, positions of Field Observation Points from coastal reconnaissance survey in 2009 and dGPS points collected for generation of improved stereoscopic models.

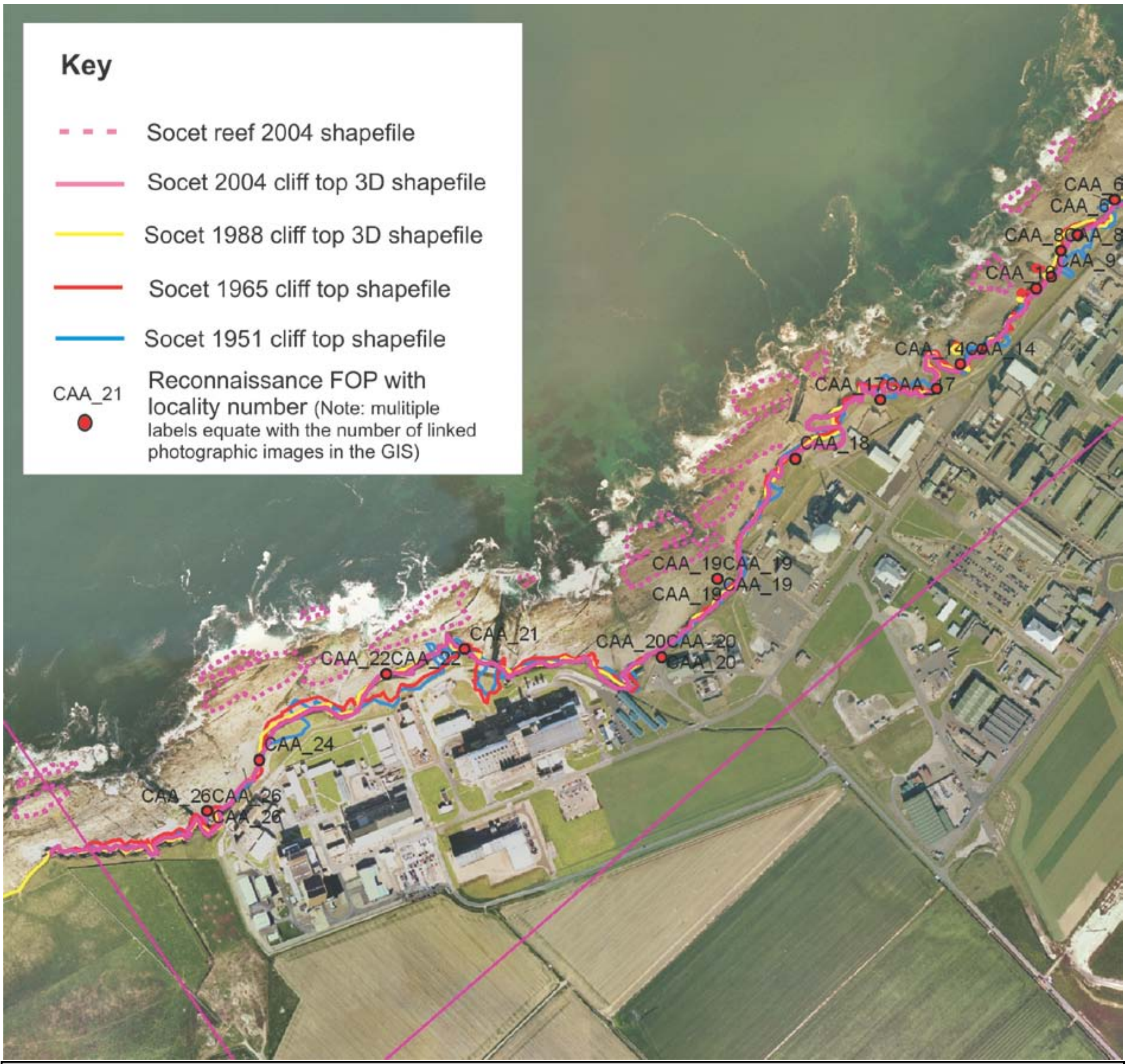


Figure 14. An example of georectified SocetSet interpretations of cliff top positions from 1951, 1965, 1988 and 2004, for the south western portion of the DS-AOI. The SocetSet rock reefs from 2004 and FOP's from 2009 are also included; all are plotted against orthorectified digital colour aerial photography, flown in 2004.

SocetSet Interpretations

139 During the Phase 1 study, georectified digital line work from the SocetSet data was confined to 'cliff top position' only, for the reasons given above. Digitising was undertaken at an effective scale of c.1: 1,000 (1 cm: 10 m resolution). This was possible because of the ability of the SocetSet equipment and software to operate at a range of magnifications. Consequently images derived from 1: 24,000 scale photography (examined at c. 1:1 resolution on the SocetSet workstation) could be digitized with similar accuracy to those produced from 1: 10,000 scale photography (examined at a lower resolution c.> 2:1). In practice, pixellation of the images meant that effective stereoscopic views at greater than 1:1 resolution make objective digitisation of features on the photographs almost impossible.

140 Pixellation also proved a limiting factor in the intricacy of the digitizing of all lines. Although the linked Arc GIS could deal with digitisation at any scale, the number of nodes, and their spacing along the polyline was restricted, to the point that when moving the cursor, succeeding nodes would still be placed on top of one another. Nevertheless, once the stereographic models were loaded, the SocetSet equipment allowed an outstanding level of coastal detail to be visualised and digitized.

141 This accuracy was considerably improved during the second phase of study when updated DEM's were calculated for the historic datasets, but the problem of pixellation of the scanned imagery remained. Pixellation and georectification errors were not present within the 2004 digital colour imagery enabling extremely accurate and detailed digitization of the coastline. The improved accuracy of the SocetSet models for the monochrome air-photo data also enabled digitization of rock reefs and stacks for all 4 vintages of photography examined.

Results

142 The shape files generated from digitising the cliff top derived from stereoscopic aerial photography were grouped in the folder **SocetClifftop**:

This contains four .shp files

1. Socet_2004_clifftop_Shapefile.shp
2. Socet_1988_clifftop_ Shapefile.shp
3. Socet_1965_clifftop_ Shapefile.shp
4. Socet_1951_clifftop_ Shapefile.shp

143 The shape files generated from digitising the foreshore rock reefs and sea stacks were grouped in the folder **Socet_reefs_stacks**:

144 This also contains four .shp files

1. Socetreef2004_Shapefile.shp
2. Socetreef1988_Shapefile.shp
3. Socetreef1965_Shapefile.shp
4. Socetreef1951_Shapefile.shp

145 Three groups of mosaic-ed orthophotographs were also generated from the georectified scans of the monochrome photography and added to the GIS:

1. Dounreay_1951/Ortho_3062.tif; Dounreay_1988a/Ortho227.tif (generated during the Phase 1 study)
2. April_2010/1965b_ortho_mosaics/1965b_mosaic_15-22_1m_v1.tif; 1965b_mosaic_15-22_25cm_v1.tif; 1965b_mosaic_15-22_50cm_v1.tif (generated during the Phase 2 study)
3. April_2010/1951b_ortho_mosaics/1951b_mosaic_4059_3059_3061-3065_1m_pa_envi_f50_bil_v1_geo.tif; 1951b_mosaic_4059_3059_3061-3065_25cm_envi_f50_bil_v1_geo.tif; 1951b_mosaic_4059_3059_3061-

3065_50cm_pa_envi_f50_bil_v1_geo.tif (generated during the Phase 2 study)

146 The orthophotographs have been produced at a much lower resolution than the original georectified imagery used in the SocetSet interpretations, and from which they were complied. The georectification of the orthophotograph mosaic is also less precise than was achieved for each SocetSet stereo pair, simply because of the number of images in each mosaic. The April_2010 orthomosaics, which cover the whole of both AOI's, were generated at 3 different resolutions: 25 cm, 50 cm and 1 m; there is little apparent increase in perceived accuracy (as viewed within the GIS) between the highest (25 cm) and lowest (1 m) imagery.

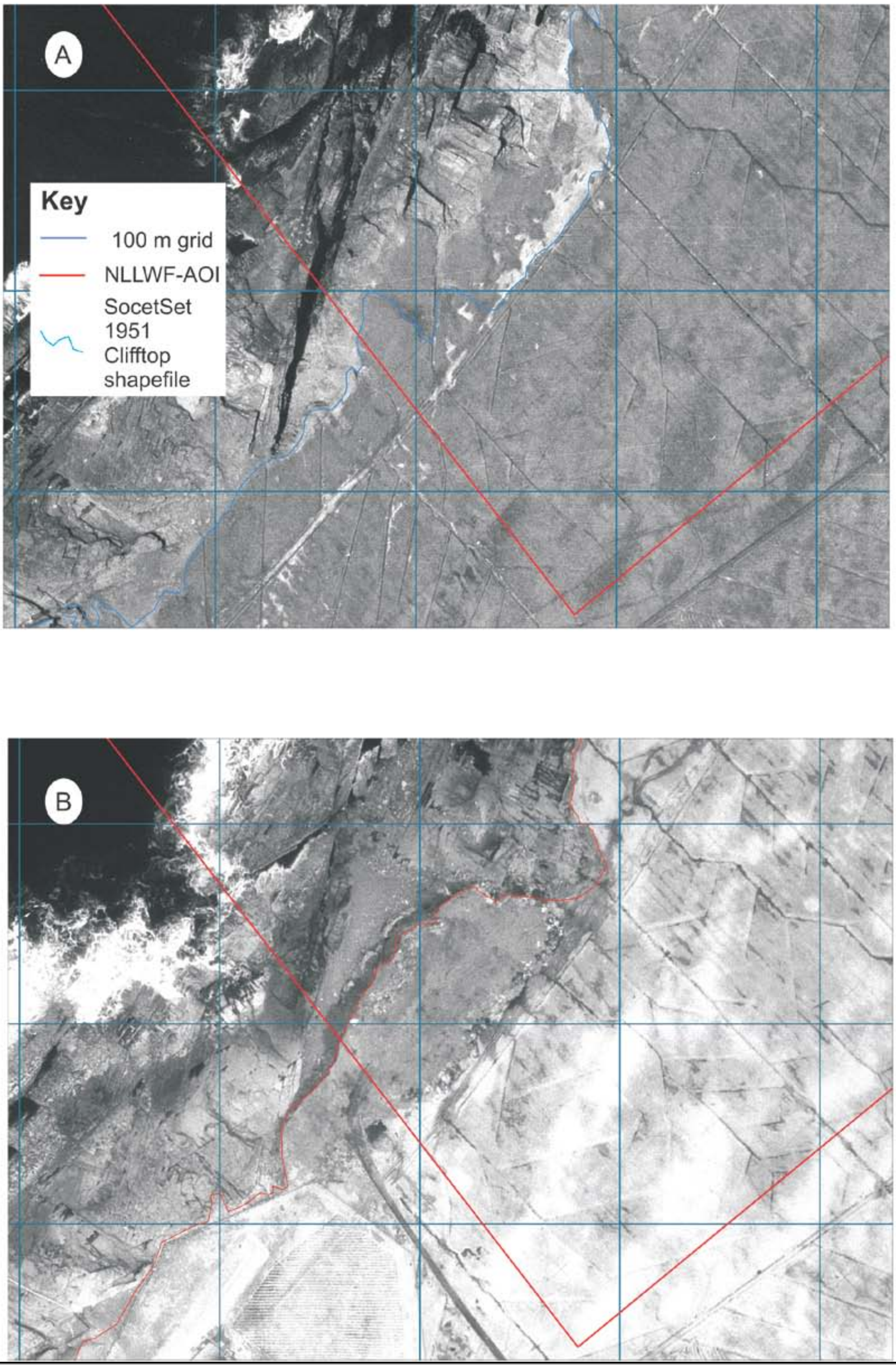
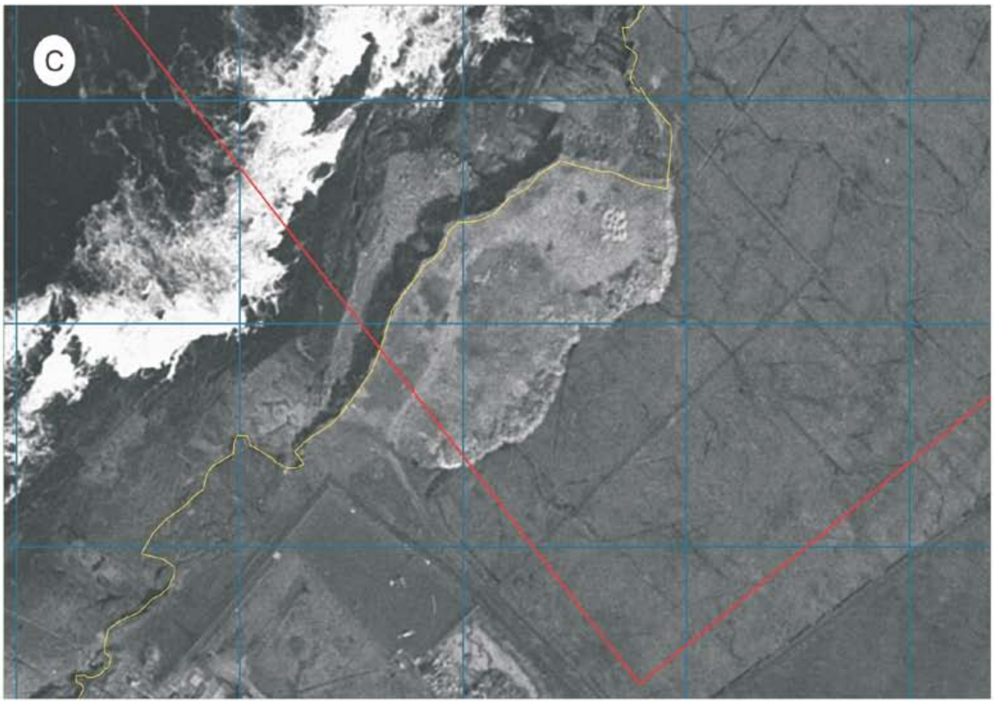
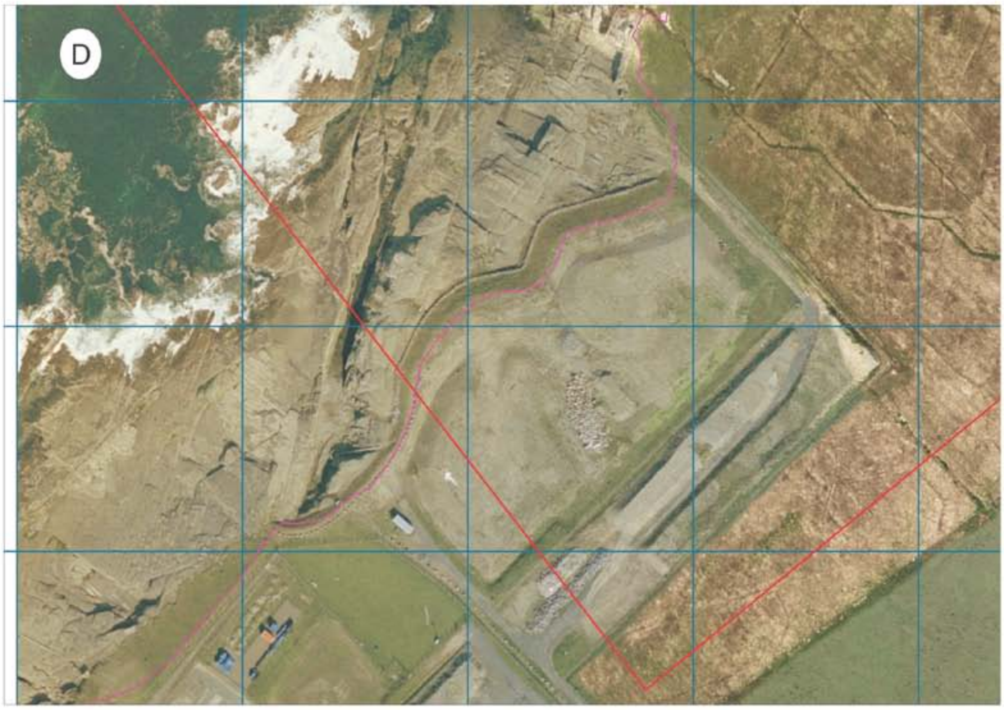


Figure 15. Changes in the position of the cliff top in the vicinity of Landfill 42. (A) blue line ~1951 cliff top; (B) red line ~ 1965 cliff top; (C) yellow line ~ 1988 cliff top; (D) magenta line ~ 2004 cliff top.


C


D

147 The monoscopic georectified digital colour aerial photographs, covering both Areas of Interest, were also added as a group **MonoAirphotos_2004** to the GIS. Each image, which covers a 1 km^2 National Grid square, can be viewed separately, or the images can be 'tiled' to provide a complete overview of the coastline.

148 All of the coastline within the NLLWF-AOI and within the DS-AOI was examined, using all four vintages of stereoscopic photography. Digitized cliff top, base of rock reef, and base of sea stack positions were created across both Areas of Interest. Direct comparisons were possible between the cliff top positions on the different vintages of photography, but this was not possible for the reefs and stacks as even a cursory examination of the imagery indicated that each photographic sortie had been flown at different, but unknown, stages of the tide. Consequently, only general comments on changes to the form of the reefs and stacks with time could be made. Interpretations of all four vintages of reef and sea stack data are therefore presented together, and separate from the cliff top SocetSet models which are described in reverse chronological order. Some duplication and repetition is inevitable when the cliff top models are compared with each other, but this is the consequence of the need to describe and explain the differences between them.

149 Particular attention has been paid to the cliff top models of two target areas: Oigin's Geo to Geodh nam Fitheach, and Glupein na Drochaide (see The Differential GPS Survey June 2008; paragraphs 92 and 94). These were also identified as requiring further study by Auton *et al.* (2009) [3]. As a consequence, although they are mentioned in some of the succeeding descriptions of the SocetSet air photo model interpretations, they have also been considered together in paragraphs 185 - 195, with the aim of elucidating the degree of morphological change that may have occurred at both localities since 1951.

2004 digital aerial photography

150 This is the most recent and accurately georectified imagery examined. It has the highest resolution (pixel size of 25 cm) despite being 'captured' at a nominal 1: 24, 000 scale. The quality of the imagery is outstanding. It far surpasses the digitized analogue data. The .tif of each 1 km x 1 km tile that was loaded into the SocetSet project exceeds 312 (Megabytes) MB in size; the resolution of each digital colour air-photo image used for illustration in this report has been massively reduced, to enable its inclusion. Each is only an imperfect approximation of the imagery used for the analysis reported here.

2004 cliff top position

151 The cliff top line was digitized along a comparable length of cliff line to that of the OS 1872/1906 and 1966/67 datasets. It was digitized in 3D (giving XY & Z values) using the terrain following capability of the SocetSet software, linked to a Digital Terrain Model (DTM) generated from NEXTMap data.

152 In general, within the DS-AOI, the 2004 cliff line lies close to its position digitized from the 1982/86 OS mapping. Its position also accords well with most of the FOP's recorded during walkover reconnaissance in September

2009 (all of which were sited seaward of the present cliff edge). These observations suggest little recession for much of the cliff seaward of the DNPE in the last 20 years. Two apparent exceptions to this are evident:

- Seaward of RN Vulcan, between [^{2}978 ^{9}668] and [^{2}980 ^{9}670], in the vicinity of FOP CAA_22, the cliff top digitized from the 2004 imagery, in places, lies up to 30 m landward of its position digitized from the 1982/86 OS survey. However, it shows little lateral displacement from the cliff top digitized from the 1988 SocetSet imagery (see Figure 14). Here the cliff is formed of made ground, so it is possible that periods of cliff recession and progradation (due to tipping) have taken place. It is more likely that different portions of the cliff profile were taken as the 'cliff edge' digitized from the SocetSet imagery to those digitized from the OS mapping.
- A more pronounced discrepancy between the SocetSet 2004 cliff position and that digitized from the 1982/86 OS mapping occurs between [^{2}990 ^{9}676] and the north eastern margin of Landfill 42 [^{2}993 ^{9}679]. Here the 2004 cliff position lies c. 25 to c. 50 m landward of the position digitized from the 1982/86 OS mapping. All of the FOP's within this area (CAA_1 to CAA_6) also occur seaward of the 2004 cliff position, but several occur between the 2004 cliff position and the cliff position digitized from the 1982/86 OS mapping. Once again, some of the discrepancies seem to have resulted, at least in part, from assigning the 'cliff top' to different parts of the cliff profile on each dataset. But a comparison of the orthophotograph constructed from the 1988 aerial photography with the 2004 monoscopic imagery shows both cliff tops are developed at the seaward edge of Landfill 42 and that the 1988 SocetSet and 1982/86 OS cliff edges, which are almost coincident, occur some 40 m seaward of the position digitized from the 2004 imagery. Even allowing for some georectification errors, it seems very probable that tens of metres of cliff recession took place in this part of the area, in the twenty or so years before 2004.

153 Within most of the NLLWF-AOI, the cliff top position digitized from the 2004 SocetSet imagery is almost coincident with the line digitized from the 1988 imagery, which is itself in very close agreement with the cliff top position from the 2008 dGPS surveying. Unfortunately, most of this ground was not covered by the 1982/86 OS survey, so the best comparisons that can be made are with the 1988 aerial photography, the 2008 dGPS survey and the 1966/67 OS data.

154 In many instances, the cliff line digitized from the 2004 imagery lies a significant distance landward of the line digitized from the 1966/67 OS data. Exceptions occur but, in most instances, this seems to have been a result of choosing different 'break of slope' positions (or ambiguous ornamentation on the OS map) for the cliff edge position.

155 The cliff top position digitized from the 2004 imagery almost always occurs landward of the position of the 'cliff edge' determined by the 2008 dGPS survey lending further support to the contention that most apparent offsets of the cliff line result from choosing different 'break of slope' positions.

156 Overall, where vertical or near vertical rock cliffs occur, the SocetSet data suggests that only limited coastal retreat has taken place in the intervening 37/38 years since the 1966/67 OS mapping. The exceptions to this may be the cliff top position in both of the 'targets' (Oigin's Geo to Geodh nam Fitheach,

and Glupein na Drochaide indentified in the Phase 1 study). Between Oigin's Geo and Geodh nam Fitheach, the cliff top position identified from the 2004 imagery lies close to, or landward of, that identified from all other cliff top datasets. It also occurs landward of all of these cliff top positions, for a distance of c. 95 m south south-westwards from the head of Oigin's Geo. However, in the vicinity of Glupein na Drochaide, the 2004 cliff lies very close to its positions digitized from all of the other aerial photographic datasets (most of which were not available during the first phase of this study).

1988 aerial photography

157 This is the best and most accurately georeferenced of the scanned monochrome photography. It is the only analogue imagery for which a camera calibration certificate was available. The cliff top line was digitized in 3D, using a DTM generated from NEXTMap.

158 As was the case with the cliff line digitized from the 2004 imagery, the 1988 cliff line lies close to its position digitized from the 1982/86 OS mapping within most of the DS-AOI. It generally plots a few metres seaward of the position digitized from the 2004 data, but no firm conclusion can be drawn regarding amounts of cliff top recession, since any difference between the positions of each line falls within the 'margin of error' caused by georectification discrepancies between the two datasets.

159 In the western portion of the DS-AOI, beyond Geo Cuinge, where the cliff profile is developed in flagstone and shows little modification by tipping of man-made deposits, the 1988 and 2004 digitized positions of the cliff top are almost coincident (see Figure14). The most obvious changes have occurred seaward of RN Vulcan and between [^{2}990 ^{9}676] and the north eastern margin of Landfill 42, as have already been mentioned in paragraph 153.

160 Within the NLLWF-AOI, between [^{2}992 ^{9}679] and [^{2}994 ^{9}682] the cliff top generally lies within a few metres landward of the line digitized from the 2004 imagery. In places however, notably the headland at [^{2}9947 ^{9}6827], the 1988 cliff line occurs c.28 m seaward of the position determined from the 2004 imagery. However, it is almost coincident with the positions determined from the 1965 and 1951 imagery, which suggests that erosion may have modified the vertical profile, rather than causing a large amount of cliff line retreat.

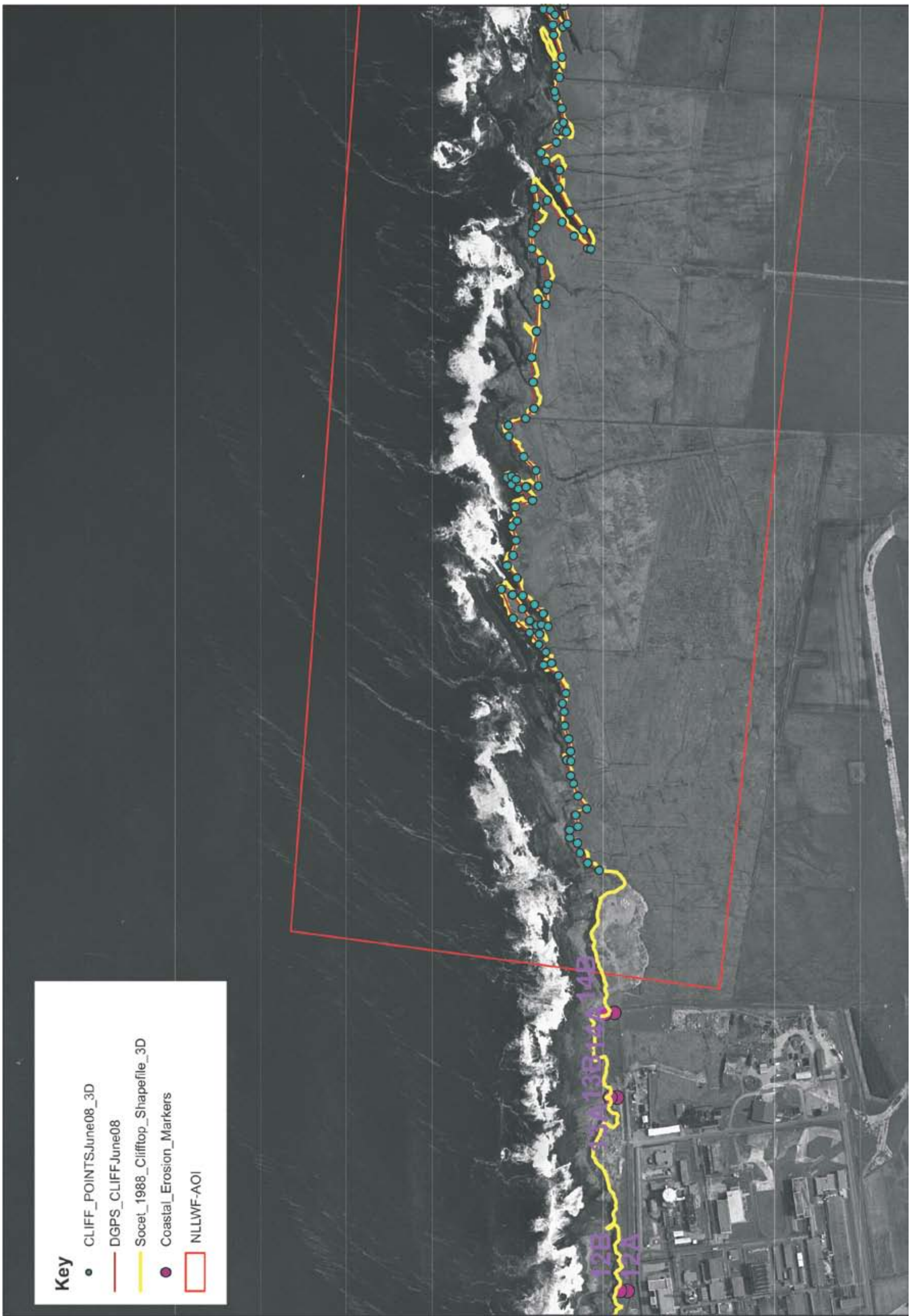


Figure 16. Orthophotograph of the coastline from 1988 aerial photography: cliff top position digitized from the SocetSet stereoscopic model.

1965 aerial photography

161 During the Phase 1 study only one stereoscopic model could be constructed of the two 1: 10,000 scale air photographs available from the 1965 OS/65/062 dataset. Unfortunately, it only covered part of the DNPE site and did not extend into the NLLWF-AOI. Nevertheless, a cliff top position was digitized for the portion of the coast north east of [^{2}988 ^{9}673] covered by the image for comparison with the 1988 cliff top position. This was not digitized in 3D because the NEXTMap DTM, generated from imagery collected in 2004, could not be reliably applied to the 1965 dataset.

162 Although only some 300 m of cliff line were digitized, there appeared to be a reasonable degree of similarity between the 1965 and 1988 positions, and some surprising minor differences and offsets. As with the 1988 data, the 1965 cliff top position generally occurred landward of both the 1966/67 and 1982 OS cliff lines. In some places, all three appear coincident, in others the 1965 and 1988 SocetSet lines were only separated by a few metres. In one instance, however, on the headland at [^{2}98879 ^{9}67491], the 1965 line is off-set 6 m north eastwards of the equivalent 1988 position. Many minor differences may be due to changes in cliff vertical profile, but those at the headland probably reflect the limitations in accuracy when comparing lines digitized in 2D with more accurate lines generated in 3D.

163 During the second phase of study, the coverage of the 1965 imagery was extended to cover the whole of both AOI's and a new orthophotograph was produced.

164 Within the DS-AOI, the cliff top position was almost coincident with that digitized from the 1966/67 OS mapping, apart from in the area of ground between [^{2}9858 ^{9}6729] and [^{2}9863 ^{9}6734]. On this ground, immediately north east of the site of the former pumping station, the position of the cliff top (which was developed in made ground) was c. 33 m landward of its position interpreted from the 1966/67 and 1982/1986 OS 1: 2,500 mapping. Again, this may be due to inconsistencies in graphic representation of the cliff top on the OS maps, especially as the position digitized from the 1965 imagery is almost coincident with that digitized from the 1987/1906 OS mapping. It is likely however, that some modification of the coastline had occurred due to erosion, as recent active erosion of man-made deposits is evident to the north east, and coastal protection measures are present immediately to the south west of the former pumping station (see FOP CAA_18, Appendix A).

165 The active erosion of cliffs developed in made ground, mentioned above, is typified by the cliff line adjacent to FOP CAA_10, where a screen of large rock blocks has been placed at [^{2}9892 ^{9}6753] to protect the cliff base. Little change is evident in cliff line digitized from the 1966/67 OS data and that digitized from the 1967 aerial photography, apart from changes in the form of the headland at [^{2}988 ^{9}675], c. 40 m south west of CAA_10. However, there is considerable evidence of cliff top recession in the air photo imagery in the area that extends c. 110 m north eastwards along the coast from CAA_10 to the vicinity of CAA_7. Here, the cliff lines digitized from the 1967 and 1988 imagery typically lie 10 to 15 m seaward of those derived from the 2004 data.

166 North east of CAA_7, the recession and periodic seaward migration of the cliff edge, resulting from the interplay between erosion and tipping of made ground

associated with the construction of the present LLWP and Landfill 42, was first identified from OS mapping. It is also clearly evident from changes in the relative positions of the cliff tops recorded from the 1965, 1988 and 2004 aerial photography.

167 Within the remainder of the NLLWF-AOI, north east of Landfill 42, the 1967 cliff top position generally shows little deviation from that digitized from the 1988 SocetSet model, although the precise form of cliff edge on some rock promontories appears to be different. This is probably largely due to illumination differences between the models. These can change the appearance of the ground, by altering the locations and intensity of deep shadows which can obscure morphological detail.

1951 aerial photography

168 Stereoscopic models were constructed from the 1951 OS/65/062 dataset of all of the 1: 24,000 scale air photographs that cover both Areas of Interest. The models show the coastline prior to the construction of the nuclear facilities at the Dounreay site.

169 The processed images are of high quality and show the natural coastline, largely unmodified by human action. Several features become immediately apparent:

- The cliff edge position in 1951 is significantly different from cliff edge recognised from the 1965, 1988 and 2004. In places, the form of its vertical profile was also more rounded than is apparent from later imagery. This is particularly true along the coast within what is now the DNPE site, where soils with a pale grey to white (bright) and 'pock-marked' appearance on the monochrome 1951 images indicate the presence of a thin, but extensive covering of blown sand (see Figure 18A as an example). This blown sand is not evident in the later imagery, where the ground surface is obscured by the buildings and roads of the nuclear establishment. However, its presence has been identified beneath made ground in shallow boreholes backing the present day cliff in the Mill Lade area of the site and has also been interpreted as occurring beneath made ground in the logs of other 'barrier area' shallow boreholes within the DNPE site (Auton, 2006) [7]; (Auton and Everest, 2007) [8].
- Within the ground now occupied by the DNPE, the rounded cliff top on the 1951 imagery generally occurs landward of the 1988 cliff top. The maximum displacement (in the order of c. 40 m), occurs in the vicinity of [^{2}990 ^{9}680]. The 1951 cliff position accords well with the cliff edge position identified on the 1955 Dounreay Site Survey (see Figure 16b); this provides independent corroboration of the SocetSet interpretation of the 1951 imagery. Several factors can explain the relationship between the 1951 and 1988 cliff positions:

    1. It is probable that, although the 1951 cliff occurs inland of the 1988 feature, it occurs at a slightly higher elevation than the latter. Much of the blown sand was probably removed from the area, either by aeolian erosion prior to the construction of the DNPE, or by excavation and landscaping during the site construction (or by a combination of all three processes).

2. The postulated elevation difference between the 2004, 1988, 1965 and 1951 cliff lines cannot be directly confirmed from the present stereoscopic models, because of the absence of good 3D control for the lines digitized from the 1951 and 1965 datasets. However, the visibly steeper vertical profile of the 1988 cliff is cut, in part, into man-made deposits largely comprising glacial till that has been bulldozed into position. *In situ* till deposits are known from borehole records to underlie landscaped deposits of sand on the present DNPE site. This stratigraphical relationship lends indirect support to the expectation of a higher elevation for a cliff top in blown sand than for one developed in reworked till that has had its upper surface truncated during construction of the DNPE site.

170 The statement given above, concerning ‘the absence of good 3D control for the lines digitized from the 1951 and 1965 datasets’ may, at first sight, appear to be counter intuitive. This is particularly true when the accuracy of positions and elevations of points on the 1951 and 1965 stereoscopic models (as given in Table 3) appear to be very accurate. This therefore, requires some further clarification. Several points need to be made:

1 The first point to note is that the accuracy values quoted in Table 3 are an average for the whole of each model and that the actual accuracy of the positional data will vary across each model.

2 Model accuracy depends <u>both</u> on the number of Common Reference Points [CRP] in the landscape that can be recognised in the past and present datasets, and the accuracy of the elevation data used to construct the DEM.

3 The portions of the 1951 and 1965 models that cover the cliff line, lie mainly within the DNPE. X-Y accuracy relates to the constructed positions of known CRP (such as ends of buildings, fence intersections etc) within the DEM for each model. Few of those that were visible on the 1951 and 1965 imagery within the ground now occupied by the DNPE are now present on the current OS topographic maps, so CRPs for comparison between the historic and recent datasets are sparse within the DNPE site area.

4 The fact that the dGPS points from the Dounreay ‘on site survey’, that were instrumental in calculating the 3D control (particularly the Z value for elevation) for the coastal portions of these models were surveyed in 1996, when much of the construction of the site had been completed (and the made ground had been laid down). This means that the elevation data for the land surface as it was in 1951 and 1965 (for the ground within the DNPE) is relatively poor.

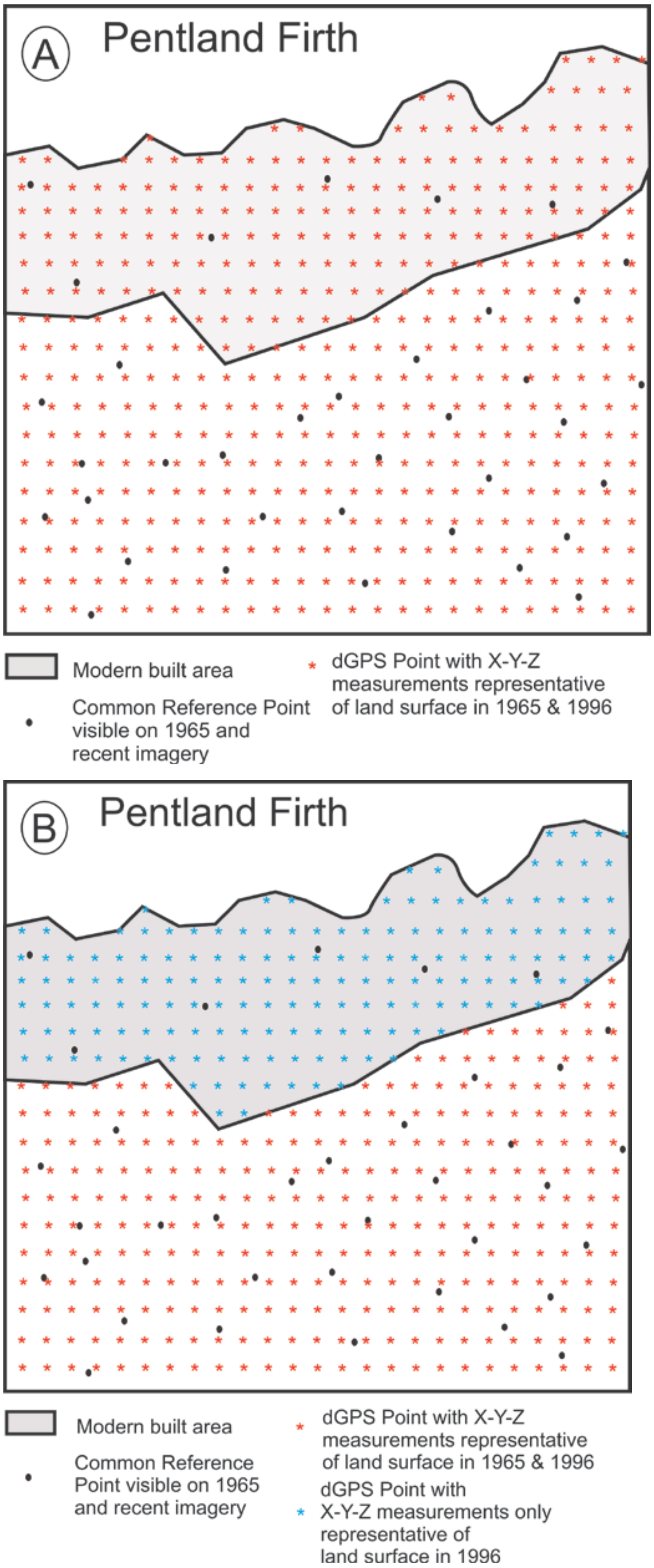


Figure 17. Conceptual diagram illustrating the causes of reduced accuracy for the modelled elevations for cliff line within the DNPE from the 1951 and 1965 aerial photography.

5 This is illustrated in two simple conceptual figures (Figure 17). In Figure 17A, within the modern built up area (equivalent to the DNPE), the density of CRP's is less than in the surrounding ground as pre existing (historic) features have been removed during construction (CRP's are destroyed, but ground surface is unchanged). Even assuming uniformly accurate representative X-Y-Z values from an equally spaced gird of dGPS measurement points (that are true representation of both the pre- and post-construction land surface) the accuracy of the part of the model covered by the built up area is less (as the CRP elevation averages more surrounding dGPS measurements than the CRP's on ground where demolition haven't taken place). The actual situation is more complex and is shown conceptually in Figure 17B. Here the number of CRP's are the same as in 17A, but the elevation measurements at dGPS points are only representative of elevation of the pre and post construction land surface beyond the built up area (red asterisks). Within the built up area, elevation measurements at dGPS points (blue asterisks) are only representative of the post construction land surface (CRP's destroyed and the ground surface has been changed); consequently, the accuracy of the modelled pre-construction land surface is much reduced in that part of the model when compared to the situation in 17A.

6 To sum up, the overall accuracy of the 1951 and 1965 models appears good, but the results are biased by the parts of each model where the ground and infrastructure remain little altered from earlier times. (there are many CRP's and little alteration to the land surface). Where major construction has taken place, CRP's have been destroyed and the measured dGPS elevations have much less relevance to former ground surface levels.

171 If these inferences given in paragraph 190 are correct, then position of the 1988 cliff line (and by analogy the position of the almost coincident 1965 cliff line) seaward of the built up area, are largely a product of the landscaping and backfilling associated with the construction of the DNPE and their location and subsequent evolution are governed by this, rather than the form and nature of pre-existing 'natural' coastline. Consequently, rates of coastal change by natural processes of erosion and slope modification that would have operated on unmodified cliff tops, between 1951 and 1988, and even until 2004, cannot be determined with any certainty in this area.

172 Another feature of the now concealed natural cliff within the DNPE site is the presence of several geos, apparently cut into flagstone bedrock. These are visible on the 1951 aerial photography but are not recognisable on any of the OS topographic maps. The best examples occur at [^{2}989 ^{9}675] and [^{2}990 ^{9}675], see Figure 17A; others occur at [^{2}989 ^{9}674] and [^{2}990 ^{9}676]. Most appear to have been infilled during the construction of the site, but their presence may be important as the surface expression of hidden zones of weakness (such as faults) in the bedrock and as zones for increased ground water movement within the DNPE site.

173 The most significant changes between the cliff top positions on the 1951 and 1988 imagery covering the DSRL AOI occur in the vicinity of Gling Glang [^{2}997 ^{9}685]. This lies within the area between Oigin's Geo and Geodh nam Fitheach, already identified from the OS topographic mapping. These will be considered further in paragraphs 183 – 195 below.

174 Within the remainder of the NLLWF-AOI, most of the changes of the cliff edge evident between the 1951 and later vintages of aerial stereoscopic photography appear to be minor. In general terms, the digitized position of the 1951 cliff edge commonly lies no more than a few metres seaward of its 1988 position; in a few instances it appears to lie slightly landward of its 1988 position. Given that the cliff line is developed mostly in bedrock, most of these latter discrepancies are probably a consequence of illumination differences between the two stereoscopic models (which marginally affects recognition and precise digitisation of the cliff edge).

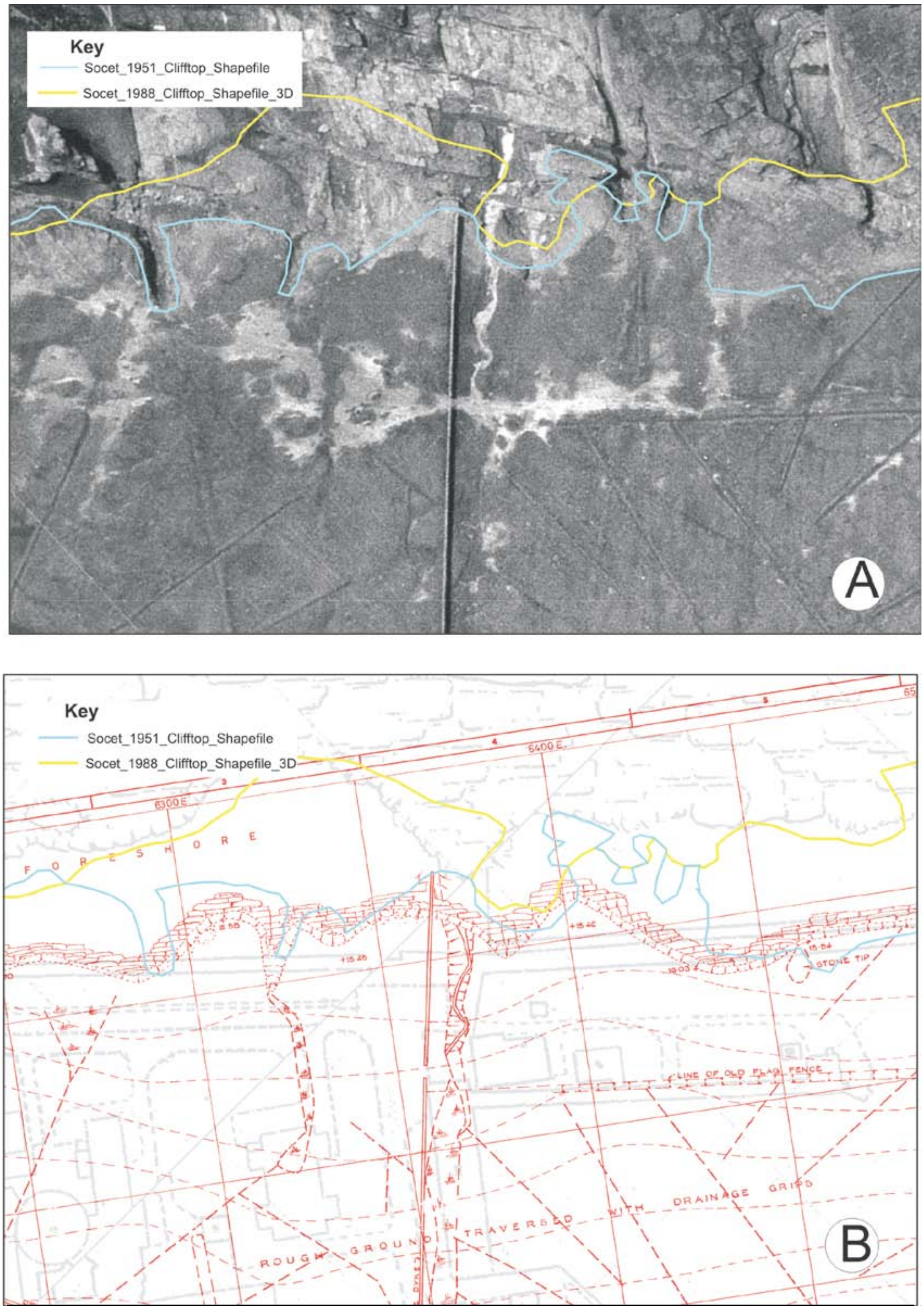


Figure 18. An example of changes in 'cliff top' position between 1951 and 1988 seaward of the DNPE site.

A ~ Blue line shows the position of a rounded cliff edge (probably developed in blown sand) on georectified stereoscopic model derived from 1951 aerial photography; yellow line shows cliff edge position developed in glacial till from 1988 stereoscopic model. Note geos developed in the 1951 cliff, especially those on the left-hand portion of the image.
B ~ Georectified positions of cliff edge in 1951 and 1988 relative to the 1955 Dounreay Site Survey cliff edge shown in red (grid at 50m intervals) and the 1982 1: 2,500 OS topographic base map (pale grey).

175 The coast around Glupein na Drochaide [^{3}00190 ^{9}68905], which was the second target area suggested for further detailed investigation in the Phase 1 study, lies close to the north eastern margin of the NLLWF-AOI. The form of the cliff top digitized from the 1951 stereoscopic model, differs in detail from those digitized from the more recent stereoscopic models. The differences appear minor and may simply be a result of illumination changes and georectification differences between the models. This is considered further in paragraphs 157 and 197

176 A more obvious change is evident in the cliff top position digitized from the 1951 data for the coastline lying immediately south east of Glupein na Drochaide. Here, the headland at [^{3}0015 ^{9}6893] lies seaward of the cliff edge position on all of the more recent aerial photographic models (and on the 2008 dGPS survey), but on the 1951 model, the digitized cliff edge position extends to the point of the headland. This is considered in more detail in paragraphs 195 to 197

Rock reefs and stacks

177 As indicated in paragraph 137, the digitized base of rock reef and base of sea stack positions were digitized across both Areas of Interest from all four vintages of aerial photography examined. However, little direct comparison could be made of changes to the morphology of each feature owing to the variation in the sea states at which each vintage of photographs were taken.

178 In general terms, all of the major reefs that were visible on the early (1951 and 1965) imagery were still present on the later imagery. Most of the stacks were also visible on all of the imagery, apart from some small stacks that were digitized at [^{2}98513 ^{9}67238], [^{2}98521 ^{9}67251] and [^{2}98608 ^{9}67319] from the 1951 imagery; these were concealed by made ground on the later imagery.

179 The appearance of each reef and stack shows subtle changes dependent not only on the state of the tide when the imagery was captured, but also the angle of illumination of the view. For example, along the foreshore between Dounreay Castle and the former pumping station site (FOP CAA_18), the form of near-shore reefs such as those at [^{2}984 ^{9}671] and [^{2}984 ^{9}672] are most clearly observed from the 2004 digital imagery. The latter is also clearly visible on the 1988 and 1965 imagery, but neither were digitized from the 1951 photography. It is also pertinent to note that the more seaward of the features appear to be more extensive on the 1965 imagery than on any of the other photography.

180 Following the observation that made ground was formerly present within the superfical deposits capping the stack near FOP CAA_8 indicating that the stack was attached to the cliff line during the late 1980's (see paragraph 114 above), all of the aerial photographic imagery covering this very small area was examined in detail, to try to determine the partial burial and exhumation history of the stack. The results are summarised as follows:

1. The stack is clearly separated from the cliff line on the 1951 imagery and the feature was digitized as a stack on both the 1951 and 2004 Socetreef shapefiles; it was not delineated on the 1965 and 1988 imagery, largely because shading partially obscured the feature on the SocetSet models.

2. The stack appears to cover a slightly larger area on the 1951 imagery than on subsequent vintages of photography; the outline of its seaward edge appears to have changed very little on all of the later photographs.
3. Photogrammatic measurement of the position of the highest point on the stack, relative to the nearest point on the cliff edge (on the SocetSet models at c. 1: 500 scale), gave the following amounts of separation: 1951 - c. 18 m; 1965 – c. 9 m; 1988 – c. 6 m; 2004 – little measureable separation (see Figure 19).

Figure 19. Stack near FOP CAA_8 and narrow headland extending from cliff line in 2004.

181 These results suggest that in 1951, prior to the construction of the DNPE, the stack was a similar distance from the cliff line to that evident during the 2009 reconnaissance survey (see Figure 11). During the intervening period, tipping associated with the DNPE construction advanced seaward until the stack became attached to the cliff line and partially buried. The stack has been subsequently exhumed, but it was still almost joined to the cliff line by a narrow headland, composed of man made deposits, as recently as 2004 (when the digital aerial photography sortie was flow). The headland has been destroyed by erosion since 2004.

182 Clearly, apart from any features buried or destroyed during the building of the DNPE, all of the reefs and stacks that are visible on the latest vintage of aerial photography must have been present when the earlier photographic sorties were flown. That some features are more evident on certain vintages of photography than on others demonstrates the degree of variability in the quality of the datasets examined, and the limits that this places on conclusions that can be drawn on the degree of coastal change that has taken place between 1951 and 2004.

183 Given the limitations outlined above, it is apparent that, although some natural modification of the foreshore must have occurred by coastal erosion between 1951 and 2004, there is no unambiguous evidence of major changes to the morphology of the foreshore (such as the complete destruction of reefs or stacks) within either of the Areas of Interest.

Assessment of the cliff top position on the headlands near Gling Glang and Glupein na Drochaide

Gling Glang

184 The possibility of significant change to the cliff top position since 1951, on the headland in the vicinity of Gling Glang [^{2}997 ^{9}685], was first recognised during Phase 1 of this study. This ground lies within the area between Oigin's Geo and Geodh nam Fitheach that was identified from the OS topographic mapping and the 2008 dGPS cliff top survey as needing further detailed investigation.

185 Although the cliff edge position digitized from the 1872/1906 and 1966/67 OS mapping extended around the perimeter of the headland, the cliff edge identified on the dGPS survey occurred inland of the promontory. The latter was therefore recognised as occurring below of the present top of the cliff profile and it was separated from the main cliff by a deep gully.

186 This conclusion was supported by the interpretation of the SocetSet models of the 1965, 1988 and 2004 aerial photography. The 1955 SocetSet model proved to be an exception. It showed the headland as a contiguous part of the cliff line and occurring at a similar elevation to that of the adjacent cliffs. This implied that a significant amount of recession of the cliff top may have occurred at the headland.

187 Unfortunately, the headland lies a few metres beyond the extent of the Off Site topographic survey data, collected in 2000, so its precise height and the depth of the intervening gully at that time are uncertain. Comparison with the adjacent Off Site contours suggests however, that the bulk of the promontory appears to be in the region of 5 – 6 m lower than the adjacent cliffs. The present elevation of the headland could be established precisely by terrestrial LiDAR scanning from the edge of the present cliff using the methods and equipment described by Auton *et al.* (2007) [2].

188 In order to investigate the possibility of cliff top retreat further, a close examination (at 1: 500 scale) was made of all of the SocetSet models of the headland. It soon became apparent that the morphology (shape and extent) of the promontory appears to have only undergone minor changes between 1951 and 2004 (see Figure 18). Patches of vegetated soil were visible on the landward side of the headland, on all four vintages of photography examined. These were very obvious on the 1951 and 2004 images; they were less clear on the 1965 and 1988 photography, due to the relatively poor resolution of the imagery. Nevertheless, there appeared to be little noticeable difference in the shape and extent of the vegetated areas between 1951 and 2004.

- To further examine possible changes in the morphology of the headland the traces of prominent breaks of slope and 'bedrock steps' developed in the exposed flagstones were digitized from each SocetSet model. These are grouped together in the folder **Gling_G_OutcropTraces** in the GIS. It contains four polyline shape files (1951_Shapefile; 1965_Shapefile; 1988_Shapefile and 2004_Shapefile).

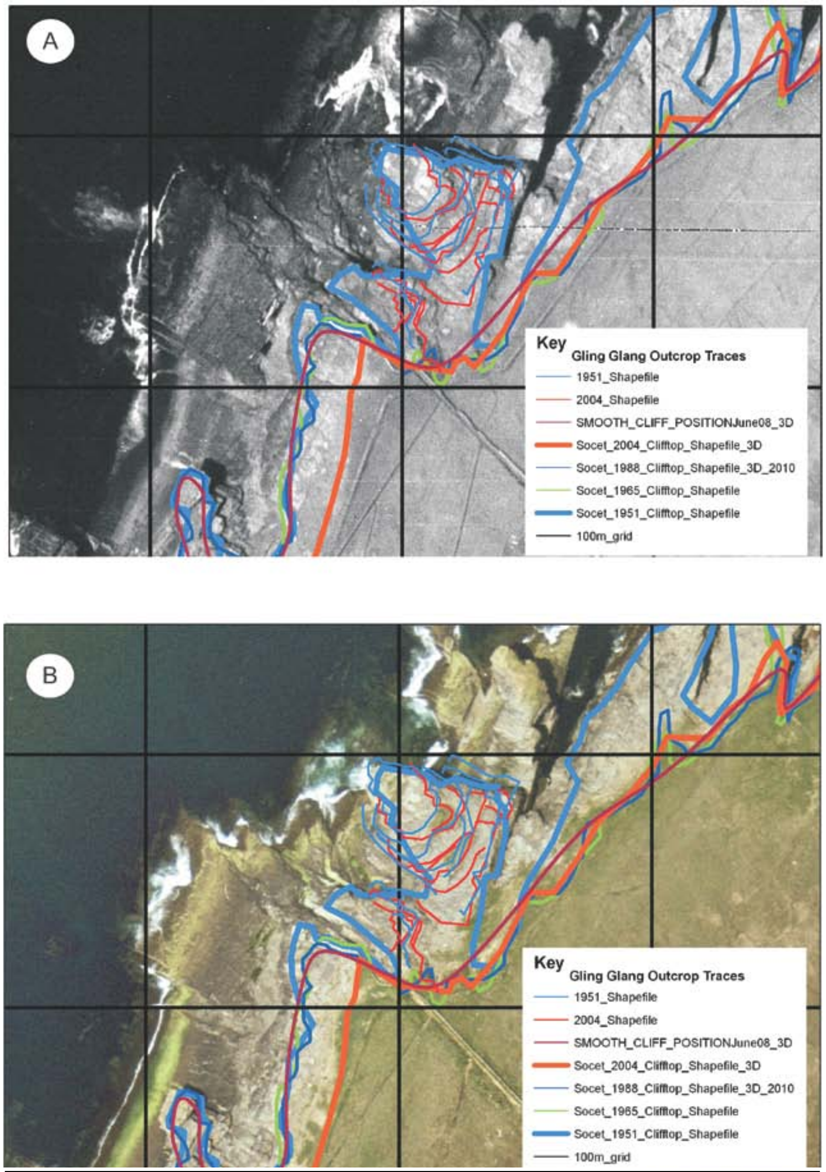


Figure 20. Orthophotographs of the headland west of Gling Glang in 1951 (A) and 2004 (B).Cliff top position lines, digitized from 1951, 1965, 1988 and 2004 SocetSet models and the dGPS 2008 cliff top line are shown on both images, in conjunction with 'outcrop traces' of flagstone ridges digitized from the 1951 and 2004 models.

189 The best data were obtained from the 1951 (Figure 20A) and 2004 imagery (Figure 20B). The positions of 1951 and 2004 'outcrop trace lines' relative to the cliff top position lines, digitized from 1951, 1965, 1988 and 2004 SocetSet models and the dGPS 2008 cliff top survey line are shown on both figures.

Minor morphological changes are apparent but, in general, there appears to be close agreement between all of the 'outcrop trace lines' on both images.

190 The gully between the headland and the remainder of the cliffs was still recognised on the 1955 imagery but it appeared to be less pronounced and shallower than on the later imagery. In fact, the gully appears to become increasingly pronounced on successive vintages of SocetSet models. This apparent deepening may largely account for the change in the interpretation of the position of the headland relative to the top of the cliff profile over time. It was clearly sufficient to exclude the headland from the cliff top line determined from the 2008 dGPS survey, but not enough to deter the OS map makers from including it within the cliff line on the 1966/67 survey.

191 The problem of the relative height of the headland (as viewed on the SocetSet model of the 1951 photography) remains. It lies within SocetSet Model 3049+3048 for the 1951 stereoscopic imagery (see Table 1) and has better than average nominal accuracy for georectification and elevation. However, this applies to the stereo pair as a whole, and relates to the dGPS calibration survey points collected in 2010. These become less numerous towards the coast and consequently the 1951 models, in particular, become less accurate as the coastline is approached. In the 1951 models, this discrepancy is increased by differences in the orientation between successive flight lines, and the non-linear lateral distortions of the scanned imagery (especially near the margins of each of the images) as well as the lack of good camera calibration data already alluded to.

192 To sum up, the detailed investigation of the headland west of Gling Glang suggests that relatively little morphological change appears to have occurred since 1951, although the gully separating it from the nearby cliffs may have become deeper and more pronounced with time. It appears to be at a stage of incipient stack formation, and the feature is included within the 'stacks and reefs. shapefiles' digitized from the 1965, 1988 and 2004 imagery. Continued deepening of the gully over time, will lead to complete detachment of the headland from the present cliff line, to form a sea stack analogous to the one at [^{2}9975 ^{9}6862] immediately north north east of the headland; both features are joined by a wave cut rock platform above MHWS.

193 A similar situation pertains to the cliff top position on the narrow headland at [^{2}9977 ^{9}6861] immediately west of Gling Glang. Here cliff top lines, digitized from the 1965, 1988 and 2004 SocetSet models and the 2008 dGPS surveyed cliff top position, occur landward of the position digitized from the 1951 photography. The latter is almost coincident with the cliff line position digitized from all of the vintages of OS mapping. In this case, close examination of the 2004 SocetSet imagery confirms that the modern cliff top is cut into superficial deposits, but the cliff edge depicted on the OS mapping corresponds to the position of rockhead. It therefore occurs some distance below the top of the present cliff profile. Close comparison of the 'outcrop trace lines' on the bedrock between the 1951 and 2004 SocetSet models again suggests that only minor modification of the cliff line has taken place, and that the cliff position has been little altered in the 53 years between the earliest and latest vintages of aerial photography examined.

Glupein na Drochaide

194 The situation at Glupein na Drochaide, close to the north eastern margin of the NLLWF-AOI, is more clear-cut. Examination of the cliff top positions digitized from all of the vintages of OS mapping and that determined from the 2008 dGPS survey were in close agreement, but were at variance with the cliff top position digitized from the 1988 SocetSet cliff model. These were the only datasets available during the first phase of this study. The subsequent extension of the 1965 and 1951 SocetSet models, as well as the one derived from the 2004 digital colour imagery, have largely resolved this issue. All of the additional SocetSet digitized cliff top positions are in close agreement with the cliff top position determined from the OS maps.

195 The discrepancy between the 1988 SocetSet cliff top line and the others is mainly due to the presence of a narrow bedrock arch, which bisects the geo at [^{3}0018 ^{9}6891]. This feature was less evident on the 1988 SocetSet model than on the other models, due to poor illumination on the 1988 images. Consequently, digitization of the 1988 cliff line was continued along the full length of the geo, inland of the arch, on the 1988 model, but it was truncated at the seaward edge of the arch on all other datasets.

196 The cliff top position on the narrow headland at [^{3}00143 ^{9}6891] some 35 m west of the Glupein na Drochaide bedrock arch is similar to that of the headland west of Gling Glang described in paragraph 188. Again, the cliff top lines digitized from the 1965, 1988 and 2004 SocetSet models and the 2008 dGPS survey, lie landward of the cliff top position digitized from the 1951 photography and the OS mapping. Examination of the 2004 SocetSet imagery confirms that the cliff top is cut into superficial deposits and rock crops out across the upper surface of the headland. Comparison of the 'outcrop trace lines' on the bedrock between the 1951 and 2004 SocetSet models indicates little morphological change has taken place on the headland, which occurs at a lower elevation than the cliff top line recognised on the SocetSet models of the later aerial photography. In this instance, the different positions of the cliff edge were simply a function of digitizing different landform features as representing the cliff edge on different models. This was due to illumination and resolution differences between the models.

Assessment of the aerial photographic investigation

197 Despite the many problems encountered, in what has been a ground-breaking approach to the use of archive air photo datasets to assess rates of coastal evolution along the complex indented coastline at Dounreay, the techniques developed in this study have great potential to establish a more accurate estimation of the former positions of the cliff top than can be gleaned from historic OS map data. The scale at which measurements of the cliff top position can be made from the air photo stereo images is, at best, in the region of a few metres. This appears particularly true of X-Y coordinates. This is less than the georectification error associated with the large-scale OS topographic data, which is commonly in the order of ± 5 m between apparently identical locations on maps of different ages. However, the problem of defining the cliff top/cliff edge position is still apparent, especially in areas where the cliff profile

is rounded. Nevertheless, the close agreement between the 3D 2004 and 1988 air photo datasets and the 2008 dGPS survey points across most of the NLLWF-AOI, lends confidence to the accuracy of the photographic models. The intricacies of the indented cliff can be recorded in greater detail using the SocetSet imagery than could be achieved by the dGPS survey with 20 m measurement point spacing.

198 The 2004 digital aerial photography produced the best imagery, both in terms of resolution and georectification. This was reflected in the clarity of the landforms that were visible and in the very close agreement between the dGPS calibration positions of features such as wall intersections, road junctions etc and their positions on the georegistered images.

199 The 1988 photography was somewhat less easy to georectify, but because camera calibration data were available for this dataset, relatively accurate models were produced using the On Site dGPS topographic point data together with the dGPS calibration points collected in 2010.

200 The 1965 and 1951 imagery was also modelled using both sets of dGPS points for calibration. Both photographic datasets lacked camera calibration information, so the model resolution was somewhat lower than for the 1988 photography. In the case of the 1951 photography, the irregular paths of flight lines across the Dounreay area were a further hindrance to constructing accurate 3D photographic models. Nevertheless, the close agreement evident between the coastline position recorded on the 1: 500 scale Dounreay Site Survey, completed in 1955, and the coastal cliff position digitized from the 1951 aerial photography, lends great confidence to the overall positional accuracy of the SocetSet model of the 1951 photography within the DS-AOI.

201 The difficulties associated with the accuracy of the elevation estimates of the non digital datasets are evident from the discrepancies between the models in the vicinity of Gling Glang, as previously described. The NEXTMap DEM used to produce elevation values for the cliff top positions from the aerial photographs was more readily applicable to the 1988 and 2004 data than to the 1965 and 1951 imagery.

202 Although it was the most difficult photography to model accurately, the 1951 imagery was of significantly better visual resolution than that from the 1965 and 1988 air photography. This is probably because it was flown at lower altitude and reproduced at a nominal 1: 10,000 scale; the 1965 and 1988 images were produced at a nominal scale of c. 1: 23,000.

3 CONCLUSIONS

203 The outcomes of this study serve to highlight the difficulties in assessing the detailed coastal evolution of the Dounreay coastline over the last 137 years using historic datasets. The most obvious difficulty is the complex coastal morphology, where steep cliffs and wave-scoured rock platforms appear to have restricted detailed topographic survey of the shoreline by the OS to two main phases: 1872 and 1966/67. The 1: 2,500 scale 1906 data for the cliff top, High and Low Water marks differ only from the 1872 data in their graphic representation on the faces of the maps. The 1966/67 survey is more accurate, defines MHWS and MLWS, and uses OD at Newlyn; the previous surveys use the Liverpool datum, meaning comparison between all of them is almost impossible. The 1982 survey was restricted to the coastline seaward of the DNPE and does not extend into the NLLWF-AOI. Given these and other limitations, notably the level of georectification accuracy possible for the OS topographic datasets (most of which were supplied georectified from OS) some overall conclusions can be made.

Coastal Changes

204 The most evident widespread changes to the morphology of the coastline have taken place seaward of the DNPE and RN Vulcan sites. Here the present cliffs are cut into unconsolidated materials. The walkover reconnaissance undertaken in September 2009, along the cliff line within the DS-AOI, showed that most of the made ground is composed of complex mixtures of building debris and glacial sediments that appear to have been bulldozed or tipped into place during construction of the DNPE and RN Vulcan sites. Tipping has also been employed as a deliberate coastal protection measure

205 . Apart from a small area of the coast in the vicinity of Dounreay Castle, where the low cliff appears to be mantled by blown sand, none of the superficial deposits exposed within the cliff line are *in situ* within the DS-AOI. The deposits which resemble glacial till contain admixtures of building debris and rock fragments and appear to be much less consolidated than is typical of tills in the Dounreay region. Consequently, the resistance of these man-made deposits to erosion is likely to be much less than that of undisturbed tills in the surrounding area. Inferences on erosion rates, based on evidence from cliffs cut in such undisturbed glacial deposits should therefore not be applied to most of the cliff line within the DS-AOI

206 . The walk over reconnaissance of the cliff line seaward of the DNPE and the dGPS survey of the cliff line within the NLLWR-AOI both suggest that large-scale cliff recession is minimal where the lower portion of the cliff profile is developed in flagstone bedrock. Although no direct measurements were made in this study, modification of the lower parts of the rock cliff profiles appears to be mainly limited to the cutting of basal notches, possible minor widening of natural arches in promontories and stacks, and minor widening and lengthening of geos (as indicated by minor changes in ornamentation between the various vintages of large-scale OS maps). Some large loose blocks have been excavated from the foreshore and now rest upon the shore platform, but evidence for widespread rapid recession of bedrock cliffs is generally absent and below the resolution of the time series of datasets considered in this report.

207 Where thick superficial deposits comprise the upper portion of cliffs more than c. 8m in height, most of the modification of the cliff profile seems to be limited to removal of vegetation cover to expose the substrate and soil, minor retreat of the cliff top and a decrease in the angle of the upper portion of the slope underlain by the unlithified material.

208 Modification of the cliff line is most evident where unconsolidated material makes up the bulk of the profile and where it extends almost to shore level. This is most evident between FOP CAA_8 and FOP CAA_9, seaward of the DNPE, where large blocks of rock have been placed at the base of the cliff to protect it from erosion. The recession of the cliff line and modification of made ground on stacks in this area has clearly taken place since the 1980's and may be ongoing. Consequently, this part of the coastline would provide a clear target for Terrestrial LiDAR scanning, to actively monitor the rate of change. This would provide unambiguous data on the rate of cliff recession and changes in cliff profile within the area in future, as scanning could be undertaken relatively quickly from the viewpoints at FOP CAA_8 and _11 (see Appendix A).

209 None of the stacks and reefs that are visible on the 1951 aerial photography have been destroyed by erosion; all are clearly present on the 2004 digital imagery (apart from two small examples close to the former cliff line which have been buried by unconsolidated tipped material). However, the stack near FOP CAA_8 (Figure 11), which stood > 20 m beyond the cliff edge at the time of the Reconnaissance Survey (September 2009) was clearly part of the main cliff line during the 1980's; it is seen to be joined to the cliff by a small promontory on the 2004 Getmapping aerial photography (see Figure 19). This indicates that the stack was at least partially buried by man made deposits during the 1980's and has subsequently been exhumed.

210 In the NLLW-AOI, most of the cliffs are cut predominantly in bedrock, with a capping of till which may only locally exceed c. 2 m in thickness. Where the rock cliffs are steep to near-vertical, any cliff recession generally appears to have been slight between 1906 and 1966/67. If present, any recession often falls within the 'noise' of the georectification errors between the OS map datasets.

Methods

211 Previous studies of coastal erosion in the Dounreay area have concentrated on many small-scale measurements on the cliff faces and foreshore, to provide an indication of possible overall rates of coastal change. Most of this work was undertaken by John Hutchinson of Imperial College, London and co-workers. The main results were presented in a series of reports to DSRL (Hutchinson, 1995 [9]; Hutchinson and Millar, 1995 [10]; Hutchinson, Millar and Trewin, 2001 [11]). These reports, which were reviewed in detail by Auton *et al*. (2007) [2], considered rates of coastal erosion both around the nuclear waste shaft and seaward of the existing LLWP. The results of these studies form the basis of the data on overall erosion rates for the Dounreay area published by Hutchinson *et al.* (2002) [1]. However, coastline modification is not uniform, as the sharply indented nature of the coast testifies. Resistant units form reefs and stacks, while zones of less resistant rock form geos and gullies. Therefore, a simple application of the rate postulated by Hutchinson *et al.*

(2002) [1] may provide an acceptable average figure across the shore line area, but it will mask significant local variations. To sum up, the erosion rate estimates and modelling produced by Hutchinson and his co workers, provided the best evaluations possible, given the limitations of the technology available at the time, and they appear reasonable, as averages, based on the results presented in this report. The main difficulty is that erosion along the coastline is not uniform, so using an average rate of erosion to calculate the amount and impact of coastal retreat on both AOI's into the future may be misleading.

212 The problems of relating former high and low water mark positions mean that the OS map data provides little useful information directly relating to larger scale changes in the foreshore area. When the cliff top, MHWS and the MLWM positions, from either the 1966/67 or the 1982 maps, are considered together, they yield important information on coastal morphology. Close proximity between the cliff top and MHWS indicates very steep cliffs, while increasing distance between the two equates to shallowing of the cliff profile. Cliff top, MHWS and MLWS positions, all in close proximity, indicate a very steep cliff that may extend below wave base. An increase in the distance between MHWS and MLWS, indicates a widening and shallowing of the foreshore profile. These kinds of observations provide additional objective criteria which would aid division of the coastal zone into areas of characteristic coastal morphology, should any subsequent more detailed characterisation and monitoring be undertaken.

213 The results of the 2008 cliff top dGPS survey are important, as they put an accurately measured limit on the position of the present cliff top within the NLLWF-AOI and because they also constrain the cliff top interpretations from the historic OS maps. Where the interpreted historic position of a cliff top within the NLLWF-AOI (and unmodified by tipping) lies landward of its position recorded from the dGPS survey points, the former is clearly inaccurate.

214 Although there have been significant difficulties in processing the historic monochrome air photography and constructing stereographic models suitable for digitising using the SocetSet workstation, the resulting imagery is often excellent. It provides a much enhanced visualisation of the morphology of the coast compared to that which can be gleaned from topographic maps. Comparison of the datasets provided by the photography flown in 1951, 1965 and 1988 produced important and accurate data on cliff top evolution in both Areas of Interest.

215 The best aerial imagery was provided by the digital colour photography flown in 2004. These fully georeferenced, high resolution (25 cm pixel) images represent the most accurate of all of the datasets covering the coastline of the Dounreay area. They produced seamless SocetSet models that enabled the cliff top position to be digitized in 3D using a linked DTM generated from NEXTMap British Elevation data, at 5 m vertical and horizontal resolution.

216 Calibration of the SocetSet models, the resultant mosaic-ed orthophotographs and also the monoscopic colour digital photographic tiles, included in the GIS, was enhanced by using dGPS point data from the Dounreay On Site and Off Site Topographic Surveys. This was supplemented by new dGPS points, collected specifically for calibration of the imagery covering the ground, at the

south western and north eastern margins of the study area, which lies beyond the ground covered by the On-Site and Off-Site Topographic Surveys.

The 1955 Dounreay Site Survey

217 Digitization of coastal features from tiled georeferenced images of the 1: 500 scale maps from the 1955 Dounreay Site survey has enhanced understanding of the evolution of coastline during the last 55 years. The survey was conducted prior to the construction of the DNPE and RN Vulcan; it shows a primarily natural coast with the cliff line unaltered by the accumulation of made ground. Several important features are apparent::

1. The position of the 1955 cliff line accords well with the cliff position digitized from the 1872/1906 OS maps. If the latter are accurate, this suggests that only minor changes had occurred during at least the preceding 49 years.
2. Where the present-day cliff line is developed in made ground, the position of the cliff line shown in the 1955 survey occurs several tens of metres landward of its position on the 1966/67 and 1982/86 OS maps. This supports the conclusion that the cliff line within most of the DS-AOI is artificial, not only in its position and extent, but also in its elevation. Consequently, because the timing of the deposition of the man-made materials is unknown, no base-line can be established against which rates of recent cliff line change can be established in much of the area.
3. Where the cliff line is unmodified by made ground, notably west of Geo Cuinge and north east of Landfill 42, its position on the 1955 survey shows little deviation from its position digitized on the 1966/67 OS maps. This again suggests little major recession of the natural cliff line in the 11 years between these surveys.
4. Ornamentations used along the cliff line on the 1955 survey maps provide an indication of the position of cliff top and the cliff base. These in turn, give an indication of the position of rock head that is now concealed beneath made ground within much of the DS-AOI. This 1955 survey data suggests that much of the ‘natural’ cliff profile within the DS-AOI was developed in flagstone bedrock and that the *in situ* Quaternary superficial deposits were thinner than the present man-made deposits. It also implies that rock head in the original cliff would have occurred at a higher elevation than the present-day contact between the flagstone bedrock and the tipped man-made deposits exposed along the present cliff line within much of the DS-AOI. This has important implications for modelling future rates of erosion and cliff recession after site decommissioning is complete.

Photogrammetric results

218 During the Phase 1 study, georectified digital line work from the SocetSet data was confined to ‘cliff top position’ only, for the parts of the 1951, 1965 and 1988 aerial photography that covered the NLLWF-AOI and georectification was hampered by an absence of camera calibration data for the 1965 imagery.

219 Although, no additional camera calibration data was available for the scanned historic photography, the fully georeferenced Getmapping digital colour 2004 imagery became available before the second phase of study. The inclusion of this new imagery allowed an accurate DEM to be created, which aided the construction of more accurate DEM's for the earlier scanned analogue images. Expanding the area of investigation (to include the DS-AOI) also increased the number of CRP's that were available for constructing the historic DEM's.

220 The acquisition of additional CRP's, from the dGPS survey conducted by Jacobs and DSRL staff, during the winter of 2010 across the ground beyond that covered in the 'site topographic survey' of 1996 and the 'of site topographic survey' of 2000, also improved the accuracy of the historic DEM's, particularly for the stereoscopic models constructed for the margins of the AOI's.

221 All of the factors outlined above mean that the second phase of photogrammetric studies produced a much more complete investigation of the record of the coastal change in the Dounreay area, than was possible from the restricted areal photographic coverage examined during the first phase of work.

222 Division of the coastline is apparent on all of the imagery. Cliffs with irregular vertical and lateral profiles cut in unconsolidated materials, are evident abutting much of the coast within the DS-AOI. Erosion of tipped material associated with Landfill 42, over time is also clearly visible, as are the steep rocky cliffs that predominate in the NLLWF-AOI. The 1951 aerial photographic survey shows the coastline prior to the construction of the nuclear facilities; thin spreads of blown sand are present on top of the glacial deposits within the DNEP area. The cliff top has a rounded profile and locally occurs up to c. 40 m inland of the steeper cliff cut into made ground visible on the later imagery. This 1951 cliff position is corroborated by the 1955 Dounreay Site Survey.

223 Overall the degree of evolution of the cliff line suggested by the topographical mapping is supported by the time series of SocetSet models produced for the air photography. Notable changes in cliff top position are evident where the cliff line is developed in made ground; changes are much less evident where the majority of the cliff profile is developed in bedrock.

224 Significant changes between the cliff top positions on headlands around Gling Glang and Glupein na Drochaide, postulated from comparisons made between the 1951 and 1988 imagery during the first phase of this study, appear to have been erroneous. The subsequent acquisition of coverage from the 1965 and 2004 sorties, corroborates the conclusion that the cliff top position, at both sites, has changed little from that digitized from the 1988 imagery. This was also supported by the cliff top position recorded during the 2008 dGPS cliff top survey. A very detailed examination of all of the SocetSet models covering both localities has been made. Some very small changes were evident, but it was evident that the topography of the features had changed little since 1951.

225 Rock reefs and stacks were digitized from all of the SocetSet models. Apart from the partial burial and subsequent exhumation of the small stack at [^{2}98910 ^{9}67533], few major morphological changes were noted. However, objective evaluation of the evolution of the features was hindered by

illumination differences between each vintage of imagery and obvious differences between the tidal state on each sortie.

226 The SocetSet data are generally far more accurate for locating past cliff top positions than the examination of OS mapping, with accuracy of the X–Y positions commonly < 2 m. This compares with georectification errors in the range of ± 5 m for the OS mapping. This greater accuracy lends a high degree of confidence to the cliff top positions interpreted from most of the SocetSet stereoscopic views. Some of the Stereoscopic models derived from the 1951 photography may be an exception; pronounced non-linear distortions were evident in the models covering the portion of the coast between the western margin of the DS-AOI and Dounreay Castle and discrepancies in the modelled elevation of headlands in the north eastern portion of the NLLWF-AOI were revealed during the detailed studies of the Gling Glang and Glupein na Drochaide sites.

Summary

227 From the conclusions detailed above, it is clear that digital photogrammetry, detailed examination of large-scale georectified topographic mapping and dGPS surveying have some limitations, individually, as tools for establishing amounts of coastal change in the Dounreay area. Taken together, however they provide a compelling picture indicating that much of the coastline has been subject to only gradual change and that significant alteration of the position of the cliff line has only occurred where most of the cliff profile is developed in superficial deposits. This largely applies to the cliffs seaward of the DNPE and RN Vulcan sites. However, as the superficial deposits forming these cliffs comprise tipped man-made materials mixed with bulldozed glacigenic sediments, the rate of cliff recession (and in some cases progradation, where comparatively recent tipping has occurred) a long-term rate of change cannot be established objectively using these methods.

228 Where the cliff line is unmodified by human activity, all of the methods indicate that little change has occurred during the last 55 years, There appears to have been some minor extension in the length and potential widening of Oigin's Geo based on comparison of 1966 and 1872/1906 OS data sets and apparent deepening of Gling Glang, based on compassion of all of the aerial photographic datasets. Some minor changes have taken place to the upper parts of cliff profiles developed in superficial deposits; profiles wholly developed in flagstone show minimal change. Future monitoring of the coastline modification should be considered, particularly where the cliffs are composed largely of tipped man-made materials, when new digital aerial photographic coverage is available. This would be a very simple and cost-effective way of assessing subsequent changes against the baseline presented here.

229 To sum up, the findings of this study provide no unambiguous evidence of noticeable recession of the natural cliff line within either Area of Interest during the last hundred or more years. Indeed, at the normal scale of field survey (1: 10,000) employed by BGS, there is no evidence that would change the surveyed position of the 'natural' cliff top from that which it occupied at the time of the compilation of the first 1872/1906 OS maps of the area.

4 REFERENCES

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5 GLOSSARY

AOI ~ Area of Interest
AOD ~ Above Ordnance Datum
BGS ~ British Geological Survey
CRP ~ Common Reference Point
DEM ~ Digital Elevation Model
DNPE ~ Dounreay Nuclear Power Establishment
DSRL ~ Dounreay Site Restoration Limited
DS-AOI ~ Dounreay Site Area of Interest
DTM ~ Digital Terrain Model
dGPS ~ Differential Global Positioning System
ESA ~ European Space Agency
ESRI ~ Environmental Systems Research Institute
FOP ~ Field Observation Point
GIS ~ Geographical Information System
GPS ~ Global Positioning System
jpg ~.Joint Photographics Experts Group
HMSO ~ Her Majesties Stationary Office
LiDAR ~ Light Detection And Ranging
LLWP ~ Low Level Waste storage Pits (present day pits, to date of the current report)
MB ~ Megabyte
MHWS ~ Mean High Water Mark of Ordinary Spring Tides
MLWS ~ Mean Low Water Mark of Ordinary Spring Tides
MSL ~ Mean Sea Level
NLLWF ~ Low Level Waste Facilities
NLLWF-AOI ~ New Low Level Waste Facilities Area of Interest
NERC ~ Natural Environment Research Council
NDA ~ Nuclear Decommissioning Authority
NGR ~ British National Grid Reference
OD ~ Ordnance Datum
ODN ~ Ordnance Datum Newlyn
OS ~ Ordnance Survey
PID ~ Point Identification (relates to dGPS data points surveyed by DSRL, in the winter of 2010, for photogrammetry)
PsInSAR ~ Permanent Scatterer Interferometric Synthetic Aperture Radar
RAF ~ Royal Air Force
RCAHMS ~ Royal Commission for the Ancient and Historical Monuments of Scotland
SIGMA ~ System for Integrated Geoscience Mapping
tif ~ Tagged Image File Format
SQL ~ Structured Query Language
UKAEA ~ United Kingdom Atomic Energy Authority

Appendix A Field Observation Point Data from Foreshore Reconnaissance

FIELD OBSERVATION POINT: CAA_1

Project: E3609R
Date Gathered: 21/09/2009 09:28:16
X: 299249.926125
Y: 967872.2598125

Comment ID	Originated From	Comment
1	FOP	Widely jointed flagstone dipping at low angle towards 100°

Photo Description: Eastern edge of Landfill 42. Looking inland from flagstone cliff.

FIELD OBSERVATION POINT: CAA_2

Project: E3609R
Date Gathered: 21/09/2009 09:49:52
X: 299147.905125
Y: 967793.572687499

Photo Description: Photo 2 Dog Track Fault looking SW

FIELD OBSERVATION POINT: CAA_4

Project: E3609R
Date Gathered: 21/09/2009 09:56:58
X: 299141.3976875
Y: 967732.836562499

Comment ID	Originated From	Comment
2	FOP	Shatter zone of fault about 4m wide. Fault strike 200°: Eastern side of zone shattered, but shattering cemented in 1 m wide unit.

Photo Description: Photo showing cemented eastern side of Dog Track Fault zone and central more decomposed clayey gouge with broken flagstone fragments

Photo Description: Close-up of same looking towards 200°

FIELD OBSERVATION POINT: CAA_5

Project: E3609R
Date Gathered: 21/09/2009 10:11:23
X: 299135.9748125
Y: 967724.16
Photo Description: Close up of clay gouge at head of Dog Track Fault geo.

FIELD OBSERVATION POINT: CAA_6

Project: E3609R
Date Gathered: 21/09/2009 10:19:05
X: 299025.3468125
Y: 967638.8966875
Description: Looking towards 220°

Comment ID	Originated From	Comment
3	FOP	Cliffs NE of this point are all in flagstone with very thin glacial drift or thicker Made Ground. Cliffs south westwards from the Made Ground edge are in bulldozed drift. Rock forms lower foreshore reefs.

Photo Description: Cliff being cut into Made Ground of LLWP. 50m SSW from photo shooting position.

FIELD OBSERVATION POINT: CAA_7

Project: E3609R
Date Gathered: 21/09/2009 10:32:04
X: 298969.781625
Y: 967586.7653125

Photo Description: Erosion of Made Ground at front of LLWP.

Photo Description: Erosion of Made Ground at front of LLWP (close up showing nature of material).

FIELD OBSERVATION POINT: CAA_8

Project: E3609R
Date Gathered: 21/09/2009 10:45:07
X: 298945.745
Y: 967563.0408125
Description: Sea stack with Quaternary cap

Comment ID	Originated From	Comment
4	FOP	Viewed looking SW. Made Ground c 5m of brown sandy till or head with blocks dipping seaward. Note: the stack was a promontory on an early cliff top line. It appears that it was joined to main cliff by Quaternary till.

Photo Description: Photograph of sea stack with cap of Quaternary sediments; against cliff cut in bulldozed glacial drift capped by Made Ground.

Photo Description: Photograph of sea stack with cap of Quaternary sediments; against cliff cut in bulldozed glacial drift capped by Made Ground. Note: made ground was noted during the 1980's within the material capping the stack.

Photo Description: Close up of cliff cut in bulldozed glacial drift capped by Made Ground.

Photo Description: Bulldozed glacial drift capped by Made Ground resting on flat lying flagstone cliff with undercut notch.

FIELD OBSERVATION POINT: CAA_9

Project: E3609R
Date Gathered: 21/09/2009 11:32:04
X: 298930.761125
Y: 967524.956812499

Photo Description: View of sea stack capped with head; looking NNW from cliff top. Note undercutting and incipient arch formation.

FIELD OBSERVATION POINT: CAA_10

Project: E3609R
Date Gathered: 21/09/2009 11:41:04
X: 298907.973125
Y: 967507.163437501
Description: sea stack and large granite boulders.
Photo Description: Sea stack viewed from SSW looking NNE. Large granitic blocks on southern side of stack (possible sea defence or fallen from cliff top).

FIELD OBSERVATION POINT: CAA_11

Project: E3609R
Date Gathered: 21/09/2009 11:54:35
X: 298827.5275
Y: 967416.425375

Comment ID	Originated From	Comment
5	FOP	Moderate yellow brown diamicton is loose & slightly friable. Possibly disturbed during building of the site. It has certainly been
		planed off at the top; contact with concrete cap is present in places beneath tipped material.

Photo Description: Made Ground about 1.5m thick on bulldozed glacial drift infilling narrow hollow in cliff top. Glacial material c 2.5m thick.

FIELD OBSERVATION POINT: CAA_14

Project: E3609R
Date Gathered: 21/09/2009 12:08:52
X: 298795.4940625
Y: 967393.933812501

Comment ID	Originated From	Comment
6	FOP	This part of the coast seems more stable than ground immediately to the NE. Less obvious erosion of superficial material than around the first stack site.

Photo Description: Small stack with thin cap of soil and glacial deposits

FIELD OBSERVATION POINT: CAA_16

Project: E3609R
Date Gathered: 21/09/2009 12:19:25
X: 298760.2005
Y: 967356.619999999
Photo Description: View of coast in front of the DNPE looking NW. Large concrete blocks in foreground. Note possible *in situ* brown till in background about 100 m NW of photo position.

FIELD OBSERVATION POINT: CAA_17

Project: E3609R
Date Gathered: 21/09/2009 12:30:16
X: 298676.4815625
Y: 967340.919375001

Comment ID	Originated From	Comment
7	FOP	At this point, it looks like all of the superficial material in front of the site has been subject to greater or lesser human disturbance. Nothing is natural. Therefore comparing pre building c 1950 to anything post 1950's, in terms of coast edge position, is probably meaningless in terms of calculating the natural rate of coastal retreat.

Photo Description: 5m face in bouldery material with clasts up to 35cm in diameter; layer of brick debris c. 4m from top of section. Wires and pipes intervene. Note: this material looked like in situ till from a distance, but it is all reworked. Note: steep stratification sloping onshore.

Photo Description: Close up of bouldery material with clasts up to 35cm in diameter; layer of interstratified bricks beneath compass.

FIELD OBSERVATION POINT: CAA_18

Project: E3609R
Date Gathered: 21/09/2009 12:51:28
X: 298549.2305625
Y: 967253.226749999
Photo Description: Former pump house site; now demolished. Sea defence infilled with 3m x 3m diameter boulders from Reay Diorite quarry. Note remnants of concrete jetties etc.

FIELD OBSERVATION POINT: CAA_19

Project: E3609R
Date Gathered: 21/09/2009 13:07:30
X: 298433.790875
Y: 967074.3286875
Photo Description: Shaft Isolation Project Raised Working Platform looking SW.

Photo Description: Shaft Isolation Project Raised Working Platform looking SW.

Photo Description: Shaft Isolation Project Raised Working Platform looking NE.

Photo Description: Made ground of reworked till about 5m thick on low flagstone ridge SW of Shaft Isolation Project Raised Working Platform. Note: gentle sloping beach on rock platform.

FIELD OBSERVATION POINT: CAA_20

Project: E3609R
Date Gathered: 21/09/2009 13:15:40
X: 298350.4733125
Y: 966957.873500001

Photo Description: Foreshore formed by Quaternary infill of channel by Dounreay Castle. Note: Drop in rock head (3 photograph panorama).

FIELD OBSERVATION POINT: CAA_21

Project: E3609R
Date Gathered: 21/09/2009 13:35:41
X: 298056.9683125
Y: 966969.2349375
Description: View looking NE from close to Gate 29.
Photo Description: Dounreay Castle Bay viewed looking NE from close to Gate 29. Note concrete groines.

FIELD OBSERVATION POINT: CAA_22

Project: E3609R
Date Gathered: 21/09/2009 13:43:58
X: 297939.566375
Y: 966932.310125001
Photo Description: Made Ground looking NE. boulders, debris and concrete blocks, up to 5m

diameter on low wave cut platform in flagstones

Photo Description: Made Ground looking SSW boulders, debris and concrete blocks, up to 5m diameter on low wave cut platform in flagstones

FIELD OBSERVATION POINT: CAA_24

Project: E3609R
Date Gathered: 21/09/2009 14:00:11
X: 297750.951375
Y: 966804.662687499
Photo Description: Made ground 2-3m thick forming cliff at back of low-angle ramp of flagstone and wave cut platform; looking SW from viewpoint.

FIELD OBSERVATION POINT: CAA_26

Project: E3609R
Date Gathered: 21/09/2009 14:10:36
X: 297672.864
Y: 966728.202125
Photo Description: Deep water-filled geo with vertical sides. Possibly modified by man. Note: wide spaced vertical tabular jointing of flagstones looking south.

Photo Description: Deep water-filled geo with vertical sides. Note: wide spaced vertical tabular jointing of flagstones (looking NW).

Photo Description: Mouth of geo with concrete jetty.