Dounreay Particles Advisory Group

Fourth Report

November 2008

Dounreay Particle Advisory Group

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FOREWORD

The Group's Third Report was as comprehensive as our knowledge then permitted, bringing together the wide-ranging aspects of particles in the environment around Dounreay. However, we identified major deficiencies in understanding and made a number of recommendations for further work to be undertaken.

Considerable progress has since been made, greatly assisted by a refreshing openness and cooperation by UKAEA, Dounreay (now Dounreay Site Restoration Limited (DSRL)).

Geological studies and important information from diver explorations have allowed the Group to examine the complexities of the Old Diffuser Chamber and its surrounding environment as a potential source for the release of particles during its future decommissioning.

As we recommended, further data have been provided on the nature, density and solubility of released particles.

Surveys of the sea bed using the remotely operated detection system, TROL, have improved knowledge of the extent and distribution of particles in the marine environment.

A refined monitoring system, Groundhog Evolution 2, for detection of particles on local beaches underwent an experimental on-beach trial by COMARE and DPAG, which confirmed a much improved performance compared with its predecessors. This has contributed to an enhancement of our understanding of the arrival and distribution of particles on the beaches.

The Group reconsidered the health implications in the light of the updated information and concluded that it was not necessary to change the boundaries adopted in our Third Report (DPAG 2006) to categorise particles as *significant, relevant* or *minor.*

Finally, we gave consideration to the monitoring required for protection of the public.

The Group comprises members having outstanding international reputations in their respective fields. Despite the heavy demands of their professional commitments, they have given generously of their time and collective knowledge. This report is a tribute to their dedication and also the unstinting cooperation displayed by UKAEA, Dounreay. As Chairman of the Group, I am extremely grateful to them. The Group is deeply indebted to our excellent Technical Secretary, Dr. Paul Dale, for his patience, enthusiasm and wise counsel. Our work has been greatly facilitated by the outstanding organisational and administrative skills of Allyson Wilson and June Moore as well as the continued commitment of Dr. Campbell Gemmell, Chief Executive of SEPA and an Honorary Member of the Group.

Professor Keith Boddy, CBE, DSc, FRSE

Chairman, DPAG

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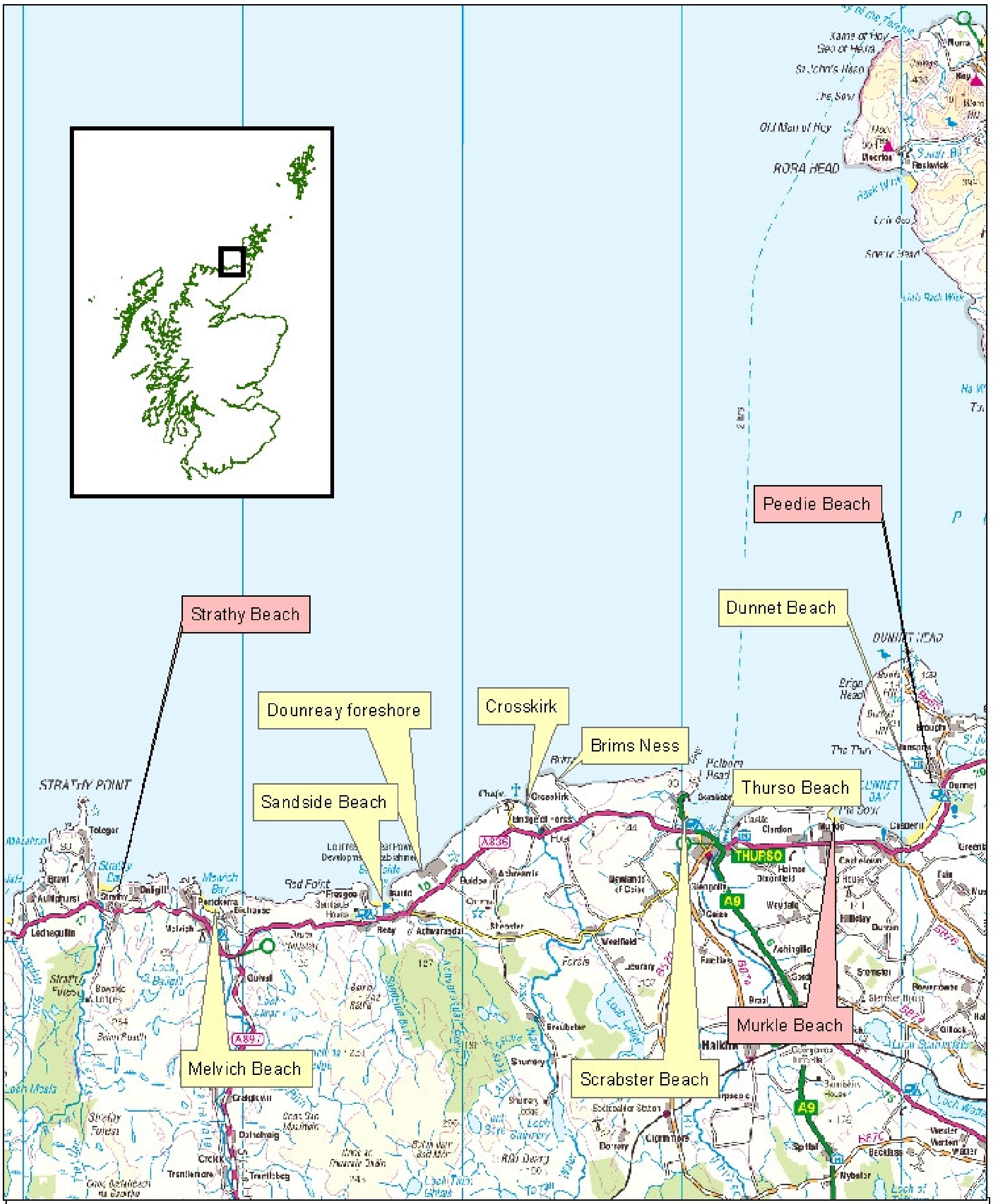

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Location of Dounreay and local beaches

0 5 10
Kilometres

SEPA
Scottish Environment Protection Agency

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Acronyms and Abbreviations

ADC	Association of Diving Contractors
BGS	British Geological Survey
CAD	Computer Aided Design
CI	Confidence Interval
COMARE	Committee on Medical Aspects of Radiation in the Environment
CPS	Counts Per Second
DFR	Dounreay Fast Reactor
(D)GPS	(Differential) Global Positioning System
(D)MTR	(Dounreay) Material Test Reactor
DPAG	Dounreay Particles Advisory Group
DSRL	Dounreay Site Restoration Ltd
FEPA	Food and Environment Protection Act
FITS	Fathoms Instrument Towed System
HCl	Hydrochloric acid
HPA-RPD	Health Protection Agency - Radiation Protection Division
HSE	Health and Safety Executive
ICPMS	Inductively Coupled Plasma Mass Spectrometry
ILW	Intermediate Level Waste
KCl	Potassium Chloride
LAD	Low Active Drain
LEDT	Liquid Effluent Discharge Tunnel
LiDAR	Light Detection and Ranging
LLLW	Low Level Liquid Waste
LLW	Low Level Waste
MHWS	Mean High Water Spring
MLWS	Mean Low Water Spring
MTR	Materials Testing Reactor

NaI	Sodium Iodide
ND	New Diffuser
NDA	Nuclear Decommissioning Agency
NRPB	National Radiological Protection Board
OD	Old Diffuser
OD	Ordnance Datum
ODC	Old Diffuser Chamber
PFR	Prototype Fast Reactor
PTFE	PolyTetraFluoroEthylene
ROV	Remotely Operated Vehicle
RWMAC	Radioactive Waste Management Advisory Committee
SEM-EDAX	Scanning Electron Microscope - Energy Diffraction X-Ray
SEPA	Scottish Environment Protection Agency
SPT	Sodium PolyTungstate
SUREC	Scottish University Environmental Research Centre
TID	Technical Implementation Document
TROL	Tracked Robotic Offshore Logger
UKAEA	United Kingdom Atomic Energy Authority

Executive Summary

The Dounreay Particles Advisory Group's comprehensive Third Report identified aspects where further work was considered necessary. This Fourth Report presents the progress that has been made in identifying potential future sources of particles, the number and distribution of particles in the marine and littoral environments and their potential health effects and the efficacy of monitoring systems.

The Old Diffuser with its immediate environment, potentially hosting a cache of particles, has been identified as a primary concern. It is recommended that further investigation is undertaken and that great care is warranted in the planning and execution of its decommissioning to prevent release of trapped particles.

Having taken account of additional studies of the properties of particles and particularly their dissolution, the Group reconsidered their potential health effects. It was concluded that the findings gave support to our three tier classification system of particles as *significant*, *relevant* or *minor* according to their potential to cause harm *via* skin contact, ingestion or inhalation.

The Group examined the results of the remotely operated TROL system for detecting particles in the marine environment. It was concluded that the ability to provide remote detection of particles with estimation of their ^{137}Cs activity and depth was a significant advance. This development provides the possibility of retrieving particles using remote equipment. We note that such systems have been trialled. The Group has welcomed the proposal by UKAEA Dounreay (now DSRL) to undertake targeted retrieval of particles from the seabed as recommended in our Third Report and the establishment of a sentry box system to provide an indication of any change in particle movements towards Sandside Beach.

A Beach Trial of Groundhog Evolution 2, undertaken by COMARE with DPAG's collaboration, demonstrated that the system is a significant improvement on its predecessors. The equipment was shown to be capable of detecting *significant* particles to a depth of 400 mm, *relevant* particles to 300 mm and *minor* particles to lesser depths.

DPAG considered the results of surveys of the marine environment using TROL. It was concluded that re-estimates of the number of particles in the main plume are similar to those derived in our Third Report. However, a larger number of particles may be in the Westward plume towards Sandside Bay than was estimated previously. It was also noted that a m*inor* particle detected further W implies extended dispersion in the marine environment.

Given the history and continuing finds of *significant* particles on the Dounreay Foreshore, DPAG reiterates the recommendation made in our Third Report that the Foreshore be closed to the public with immediate effect. The area should be monitored appropriately to provide insight into any change that might be occurring Offshore and to reduce the risk that these particles pose to human health.

At Sandside Beach, when the annual rates of finds are appropriately normalised for area, frequency and detection capability, there is no evidence of a change year by year. However, when account is taken of the improved monitoring system and the area and depth currently monitored, the estimated number of *relevant* particles in a given mass of sand is about four times greater than the value derived in our Third Report. On this basis, the estimated probability of a person encountering a *relevant* particle *via* contact with the skin would be about one in 20 million per year; the corresponding probabilities for ingestion and inhalation are several orders of magnitude less.

No *significant* particle has been found so far on Sandside Beach but, if one were present, the probability of skin contact in a period of two weeks has been estimated as about one in 60 million.

The minimum criterion for the protection of public health could be satisfied, in principle, by a scheme in which the entire Sandside Beach was monitored twice yearly. In practice to achieve this, the beach must be monitored on a much more frequent basis. However, DPAG recognises that particles might be mobilised during operations for their retrieval from the seabed, as a result of decommissioning procedures or the resumption of fishing activities if the FEPA Order were to be rescinded. The Group notes that any effect of mobilisation close to the Old Diffuser (OD) might not give rise to increased arrival rates at public beaches for several years. Consequently, the Group reiterates the recommendations in our Third Report (DPAG 2006) that monitoring at Sandside should be undertaken fortnightly. It is recommended that the beaches at Brims Ness and Crosskirk should be monitored quarterly and those at Melvich, Murkle, Peedie, Thurso and Scrabster be monitored annually and the results subject to periodic review. Areas of Dunnet Beach most frequently used by members of the public should be monitored on a quarterly basis until such time that these areas can be reviewed in the light of a habits survey.

Provided that monitoring and recovery of particles occurs at the frequencies recommended, DPAG considers that the continuing rates of detection and level of activity of particles on these beaches do not pose a significant risk to the public.

1. Introduction

1.1 Background

1.1.1 The background to the establishment of DPAG, which was set up by UKAEA and SEPA in May 2000, is given in our Third Report (DPAG 2006).

1.1.2 Our previous report (DPAG 2006) brought together the diverse aspects of radioactive particles in the environment around Dounreay and provided an integrated overview as far as extant knowledge permitted. For ease of reference, our Conclusions, Recommendations and Proposals for Further Work are reproduced in Appendix 1.1.

1.1.3 Having considered the report, SEPA asked the Group to undertake additional work in a programme focussed on the following areas:

- Potential for future sources of particles;
- Particle characteristics and behaviour;
- Evaluation of the tracked performance of detection systems including:
  - Current, past and future extent of contamination;
  - Evaluation of Tracked Robotic Offshore Logger (TROL) and subsequent particle recovery systems;
  - Commentary on the arrival of particles on public beaches;
  - Commentary on the adequacy of existing monitoring. Work on this area should clearly differentiate between monitoring needed for protection of the public and monitoring undertaken to quantify the extent of the contamination.

1.1.4 This Fourth Report presents the progress made in these areas.

1.2 Potential for Future Sources of Particles

1.2.1 The Group has updated previous findings, paying special attention to the Old Diffuser (OD) system and its surrounding rock with particular reference to its decommissioning.

1.3 Particle Characteristics and Behaviour

1.3.1 Our Third Report identified the need for measurement of the density of released particles. This characteristic, together with mass, size and shape, is essential in understanding the extent to which the behaviour of particles in the marine environment resembles that of sand grains. Additional work on particle characteristics has been undertaken.

1.3.2 In testing the solubility of particles under simulated physiological conditions, it was noted in our Third Report (DPAG 2006) that one particle differed significantly from the others. Immediately prior to completion of that Report, the Group learned that the particle might be of a different composition, uranium oxide. Further work on the solubility of particles has now been undertaken and is reported here.

1.3.3 The extent to which a particle might lose some of its radioactivity to the surrounding sand has also been investigated.

1.4 Performance of Detection Systems

Evaluation of Marine Systems

1.4.1 An analysis of the detection capability of TROL has been undertaken, including its ability to assess simultaneously the activity and depth of a detected particle.

Evaluation of Beach Systems

1.4.2 Since our previous report, the Groundhog monitoring system has been further developed as Groundhog Evolution Mark 2. With the collaboration and participation of the Group, COMARE undertook a Beach Trial of the new system, analogous to that reported earlier for Groundhog Mark 1 and Groundhog Evolution.

1.5 Extent of Contamination of the Marine Environment

1.5.1 The availability of results of monitoring the marine environment during 2006 and 2007 has enabled the Group to update its previous assessment.

1.6 Arrival of Particles at Public Beaches

1.6.1 As suggested by the Group, the beaches at Murkle and Peedie have been monitored three times. Three further surveys have also been undertaken at Dunnet Beach.

1.6.2 Although monitoring of Sandside Beach was interrupted for several months during 2007, the available results have provided further insights. The Group has considered analyses aimed at assessing whether particles detected on Sandside Beach were ‘historical’ in nature or ‘new arrivals’.

1.7 Health Implications

1.7.1 The implications for health of additional information on dissolution of particles and the frequency of ‘arrivals’ of particles at Sandside Beach have been considered.

1.7.2 Making the assumption that a *significant* particle is on the beach at Sandside, the probability of contact with it has been assessed.

1.8 Monitoring Required for Protection of the Public

1.8.1 Based on this review, the monitoring needed for protection of the public and to quantify the extent of contamination has been reconsidered.

2. Potential Sources of Future Releases of Particles

2.1 Introduction

2.1.1 In this Chapter we seek to identify locations from which particles could inadvertently be released during decommissioning.

2.1.2 Our Third Report (DPAG 2006) referred to UKAEA investigations into on-land, potentially persistent sources and routes of release of particles to the marine environment, and to the published consideration given to these by RWMAC (1999). These sources and routes included: a) roadways, verges, loading bays and soil; b) roofs, gutters, gulleys and surface-water drains; c) cliff overburden and cliff faces; d) the Dounreay Foreshore; e) the Sea Tanks; f) the Wet Silo; g) the Low-Level Waste Disposal Pits; h) the Shaft to which large amounts of the metallic swarf produced during fuel reprocessing between 1959 and 1977 had been consigned. Most of these installations/locations are represented on Figs 2.1, 2.2 and 2.3. Our Third Report's (DPAG 2006) analysis of the plume of particles that had been identified offshore on the sea bed led to the conclusion that discharges from the Old Diffuser (OD) had been its primary offshore source.

2.1.3 A conceptual diagram indicating the liquid discharge routes through the UKAEA establishment for MTR and DFR particles from their point(s) of origin to the OD and thence to the sea bed, comprises Fig. 2.2 of our Third Report (DPAG 2006). It is reproduced here as Fig. 2.1, in a slightly modified form. Tracing the routes, represented on Fig. 2.1, that were followed by the particles through the UKAEA establishment from the site of their initial generation during reprocessing, *via* the Low Active Drain (LAD) and the Sea Tanks to the OD, is a key to identifying those intermediate sites where particles could have been trapped. Other routes for particle escape and entrapment, most of which could be regarded as distributaries from the direct route followed by the particles from the DFR and MTR re-processing plants to the OD, include the Shaft, the Wet Silo, the Low-Level Waste Disposal Pits, Non Active Drains, gulleys, roofs and gutters. In addition, because local, slightly enhanced radioactivity has been detected there, including a particle discovered in June 2008, Landfill 42 must be included as a site potentially containing further particles.

2.1.4 Fig. 2.2 shows the installations that comprise potential particle sources on the site and the route of the Low Active Drain (LAD). Fig. 2.3 is a map of the route of the Non-Active Drains also showing the routes followed by the flasks that carried the swarf produced by the reprocessing of fuel from its point(s) of origin to the Shaft where much of it was disposed of. Fig. 2.4 shows the offshore site of the OD and its links to onshore facilities. Fig. 2.5 shows the configuration within the Old Diffuser Chamber (ODC) of the four 254 mm cast-iron pipes that had carried effluent discharged from the Dounreay and Vulcan[1] sites along the Liquid Effluent Discharge Tunnel (LEDT). It also shows the 16 short sections of mild steel pipes connected to the top of the cast iron pipes that originally carried the effluent *via* the unlined risers to the sea floor, ~23 m above the roof of the ODC. Fig. 2.6 shows the door separating the ODC from the tunnel. The original engineers' drawing of the ODC and the pipework within it is reproduced in Figs A2-1a and A2-1b.

2.2 Potential Sources of Particles Onshore During Site Restoration

2.2.1 **Transport of Swarf** Swarf derived from the crushing, cropping or milling of fuel elements as a precursor of reprocessing was transported in flasks across the Dounreay site for disposal in the Shaft. The routes followed by the open flasks are shown in Fig. 2.3. Windy conditions, from time-to-time, must have distributed swarf, including some radioactive material, on the Site. Some lodged on roadways, verges, loading bays and soil. Such incidents involving the spillage of swarf could, thus, have been the source of the particles that constituted the "hotspots" that were recorded in 1964-5 surveys of the Site (Walford 1995). The 79 particles, found on site up to 1999 and discussed by RWMAC (1999), probably had a similar origin. Particles were not found on roofs, gutters or gulleys. The small quantities of swarf particles found on the open spaces on site (categories a and b in Fig. 2.1), despite intensive, on-going site monitoring, suggest that these sites are unlikely to yield many particles during decommissioning.

2.2.2 **Non-Active Drains** Particles dispersed during the transport of swarf in windy conditions could have gathered in the open drains (Fig. 2.3), designed for rainwater dispersal, or at least those drains that were in existence in the 1960s. A cache of particles was known to exist (see 2.2.3 below) in a drain in the DMTR complex (Fig. 2.2) which has now been isolated. This and the possibility of wind-borne particles (see above), suggest that parts of the Non-Active Drain system cannot be ruled out as a source of particles during decommissioning.

2.2.3 **Low Active Drains** There are two generations of Low Active Drain (LAD). In the late 1970s the original LAD was isolated in concrete and a new LAD, following the same route as the old LAD, was laid on top of it. Connections to the LAD conveyed liquid waste from facilities to the LAD; the connections associated with the DMTR pond, now isolated, are known to contain particles and believed to contain thousands of particles. By the DMTR pond, two tundishes were connected to a Non-Active Drain. This drain is known to contain particles as noted in 2.2.2.

2.2.4 Effluent from the Shaft was pumped, unfiltered until 1985, to the LAD to maintain the Shaft water level below sea level; this water could have been

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[1] The MoD disposes of liquid waste from HMS Vulcan to UKAEA and this enters the UKAEA collection system at the boundary fence, intermixing with the UKAEA's own liquid waste. UKAEA is wholly responsible for the management and disposal of the liquid waste once it enters their collection system.

carrying particles, especially during periods when, at the same time, swarf disposals to the Shaft were being made. Similar circumstances existed at the Wet Silo.

2.2.5 Appendix D of DPAG 2006, records events in the course of which particles are known to have entered the LAD system, and on occasion the Non-Active Drains.

2.2.6 **The Cliff Overburden and Cliff Faces** (category c) have been surveyed periodically since 1996, and having yielded only one *relevant* particle, it is concluded that these localities are extremely unlikely to be a significant on-going source of particles.

2.2.7 **Dounreay Foreshore** (category d) Analysis of offshore particle distribution reported in detail in our Third Report (DPAG 2006) concluded that the particles found on the Dounreay Foreshore, many of which are *significant,* are not sourced directly from the Site or from the adjacent cliff. In August 1996, most of the sand on the beach was systematically excavated, monitored and replaced. The particles subsequently found there are believed to come from the sea bed whence they are carried onshore from the particle plume by powerful waves but are abandoned on the shore because of the diminished force of the retreating swash. The Dounreay Foreshore, therefore, is considered to be a recipient rather than a source of the particles in the marine environment. As such, monitoring and particle removal will have to continue and due to the number of *significant* particles found, public access should be prohibited.

2.2.8 **Sea Tanks** (category e) Having considered all potential sources and routes of particle escape in our Third Report (DPAG 2006), DPAG concluded that the most likely route for the historic discharge of particles to the marine environment was *via* the LAD, Sea Tanks (Low Active Liquid Effluent Tanks) and the LEDT and thence to sea from the OD. Our Third Report (DPAG 2006, pp 15-16) identified the Sea Tanks (Fig. 2.1) as a major source of the particles that had found their way to the OD *via* the pipes housed in the LEDT. Sludge, containing an unknown quantity of particles that had settled in the Sea Tanks, was, in the first two years of operation, agitated by high-pressure hosing and was discharged with the liquid effluent to the OD. This undoubtedly contributed largely to the historic particle discharges through the OD. Although the D1211 tanks and ducts were cleaned out prior to 2004, it is possible that small quantities of such sludge containing particles could still be present in the facility and, as such, may be encountered during decommissioning.

2.2.9 **The Wet Silo** (category f) is used to store ILW; considerable quantities of swarf are known to have been consigned to it. Thus the Wet Silo emerges as a potential source of particles that would be encountered during decommissioning.

2.2.10 **The Seven Low Level Waste pits** (category g) (Figs 2.1 and 2.2) lie some 32 m from the cliff edge to the Northern part of the Site, and as such are vulnerable to longer-term erosion by the sea. There is no reliable/comprehensive inventory of their contents, described in our Third Report (DPAG 2006, p. 14) as compacted, non-compacted, drummed and bulk wastes. It has not been established that the wastes contain particles but the presence of particles seems likely. They certainly received lower-activity sludge from the Sea Tanks.

2.2.11 **Landfill 42** is licensed as a landfill site for inert waste only; it lies just outside and to the E of the Dounreay site and is believed to consist of ~50,000 m^3 of builders' waste and construction spoil, originating from the Dounreay site. However, it is known to contain radioactive waste. Surveys of the Landfill (March-June 1999) revealed five *minor* particles. A further *minor* particle was found in June 2008.

2.2.12 **The Shaft** The position of the Shaft is shown on Fig. 2.2. Very large quantities of swarf were consigned there during its period as an ILW disposal site. It is 64.5 m deep and has a diameter of 4.6 m. The Wet Silo was constructed to replace the Shaft as a disposal facility in 1971, although the latter continued to be used as such until 1977.

2.2.13 A comprehensive programme of Shaft decommissioning is in progress. This has involved:

a) A programme of drilling boreholes and grouting to isolate the Shaft from the LEDT (October/November 2006);

b) A programme of drilling boreholes and grouting in an inner ring around the Shaft (January-April 2007) to isolate the Shaft contents;

c) A programme of drilling and grouting in an outer ring around the Shaft designed greatly to reduce the flow of groundwater into the Shaft was completed in 2008, and;

d) Hydrotesting has been completed to determine the efficacy of the grouting and to discover if further grouting is required.

2.2.14 This programme will enable the emptying of the Shaft of its retrievable contents and their engineered containment as ILW and LLW to proceed.

2.2.15 It is believed that six tonnes of swarf were disposed to the Shaft, comprising many million individual particles, although most of these would have been aluminium only. From time to time, therefore, it has been a favoured source for the particles present in the marine environment. A report by RWMAC (1999) concluded, however, that "it is extremely unlikely that particles can migrate *via* any natural fracture flow system through the mass of the Caithness Sandstone Group" which would be implied had particles escaped from the Shaft *via* interconnected pathways in the rocks in which the Shaft and LEDT had been constructed. Our Third Report (DPAG 2006) endorsed this conclusion, following further detailed consideration of post-1999 geological and hydrogeological evidence relating to the Shaft as a potential and on-going source of offshore particles.

2.2.16 The Shaft itself is now isolated from the rock mass as part of the programme of decommissioning (see a-d above), precluding any putative further escape of particles. If, however improbably, passage of particles through the rock mass from the Shaft to the sea bed had already been in progress at the commencement of isolation work, then any particles located outside the new grouting ring would be likely to continue their migration. They might then form a continuing discharge to the sea bed that would be expected to diminish with time. Considerations of the conditions required for moving particles along fractures to the sea bed suggest that their physical size would be small compared with many or most of those recovered from offshore.

2.3 The Old Diffuser (OD) as a Potential Offshore Source of Particles

2.3.1 Because of its physical condition (see below) and known role in the historical discharge of particles (DPAG 2006), the Nuclear Decommissioning Authority (NDA) and Scottish Environment Protection Agency (SEPA), as the regulatory authority, have expressed a preference for early decommissioning of the Old Diffuser Chamber (ODC). This section describes the design, construction and functioning of the OD system and seeks to predict the general location of particles in its immediate environment; from this the risk of particles being released to the environment, from the OD system during such decommissioning may be assessed.

2.3.2 **Design, construction and functioning of the OD** The OD is situated at the downstream, seaward end of the system by means of which authorised discharges of Low Level Liquid Effluent from the Dounreay Site and HMS Vulcan were made to the sea (Fig. 2.4). It comprises a concrete-lined chamber (ODC) (Figs 2.5 and 2.6), 4.5 m wide x 10.0 m long x 3.7 m high that had been excavated in solid rock, dominantly sandstone. Its roof, sometimes referred to by the engineers as its “soffit”, is ~23 m below the seafloor which, at the time of its construction, exposed solid rock. The ODC was connected to the sea bed by sixteen unlined vertical boreholes known as “risers”.

2.3.3 It was constructed some 595 m NW of the Shaft at the NW end of the LEDT which slopes upwards towards it at a gradient of 1:200 from the base of the Shaft. The LEDT was isolated from the base of the Shaft by a concrete plug (Fig. 2.4) once construction of the system had been completed. The ODC was connected to the discharge tanks by four nine-inch (~229 mm) internal diameter, spun-iron pipes that originated in the Low Level Liquid Effluent Tanks (the “Sea Tanks”).

2.3.4 These pipes are still in place and pass *via* an inclined tunnel from the ground surface within the Establishment, down to the LEDT (Fig. 2.4). This inclined tunnel is known as the Adit which must itself be regarded as a potential source of particles. Within the LEDT, the pipes are encased in a ~1 m square section concrete haunch (Fig. 2.7) running along the base of the NE wall of the Tunnel. At the far end of the LEDT is a concrete bulkhead wall with an iron door providing the entrance to the ODC (Fig. 2.6). The door was closed and barred before the whole system was allowed to fill with water after construction had been completed. Limited movement of water can still occur between the LEDT and the ODC around the edge of the closed door and/or through a former drain opening at the foot of the concrete bulkhead. The four cast-iron pipes are exposed for a few tens of millimetres between the end of the concrete haunch and the bulkhead, to accommodate gate valves.

2.3.5 In the ODC, the pipes are exposed as two pairs, each pair running above the floor of the ODC along the opposite NW-trending walls of the ODC. Within the ODC, every pipe is connected to the rock above the roof by four vertical, mild-steel riser pipes (Fig. 2.5). There are sixteen risers in total. There is no designed cross-over from any nine-inch pipe to the risers fed by a different nine-inch pipe.

2.3.6 Within the rock mass above the roof of the ODC, the risers consist of boreholes drilled vertically upwards from the ODC to the sea floor (Appendix 2.2). The lowest 10 feet (3 m) of these holes were drilled to a diameter of five inches (~127 mm) and mild-steel tubing with three-and-a-half-inch (~89 mm) internal diameter was set in each hole and grouted in place. These liner tubes had a flange at their lower end; a drill was introduced through each liner and used to bore a three-inch (~76 mm) diameter hole upwards through rock to the sea bed. These holes were not lined, so the walls of the risers are unprotected rock through most of their height. Every hole was temporarily plugged at the sea bed while other holes were drilled and pipework completed. Connecting pipes were later attached to join each riser to its nine-inch feeder pipe from the LEDT, but not before the temporary plugs had been removed and a short length of flanged steel tube inserted into each riser and grouted in place to form an upstand about 600 mm high above the rock outcrop on the sea floor.

2.3.7 All of the sixteen risers that had discharged effluent to the sea floor were sealed, either with lead plugs placed in 1999/2000, or by concrete placed during construction of the New Diffuser (ND). This concrete overspill was removed a couple of years later and revealed the three risers that had been covered.

2.3.8 Historical discharges *via* the OD satisfactorily explain the distribution of particles offshore and our Third Report (DPAG 2006) concluded that it was the main discharge route for particles that reached the sea. The condition of the discharge system had given rise to concern from 1979 onwards, leading to its replacement by a new structure on the sea bed – the ND, commissioned in November 1992 – with completely new discharge pipework feeding it *via* the LEDT. One of the old pipelines feeding the OD remained operational, however, and was used monthly until June 1997.

2.3.9 The efficiency and integrity of the OD had become suspect by the early 1980s based on divers' inspection of the riser upstands and divers' reports on dye tests on the sea bed in the vicinity of the ODC roof (Appendix 2.2). An ROV inspection in 1989 of the distal (ODC) end of the LEDT recorded conditions there, during effluent discharge, that could imply damage to pipework within the ODC, (Appendix 2.1) and possibly, therefore, the release of particles into the ODC itself. These and later investigations, (see 2.3.3 and Fig. 2.12), imply that there is, and has been over several years, considerable interconnective fissuring of the rocks containing the unlined risers above the ODC as well as the possible damage to the pipework mentioned above and discussed in Appendices 2.1 and 2.2.

2.3.10 The geological strata comprising the ~23 m of rock intervening between the roof of the ODC and the sea floor include several shallowly inclined layers (beds) that would have been vulnerable to attack by the nitric acid effluent (see 2.3.12

below), as would any steeply inclined fault zones or fault-related joints and fissures originally containing or lined by carbonate, probably calcium carbonate. Interconnected fissuring along steeply dipping vulnerable zones intersecting shallowly dipping vulnerable zones would inevitably have resulted. The potential interconnectivity of such planes is shown by Fig. 2.9. Furthermore, the cementitious grout that had been used to render the rocks impermeable to water before the drilling of the risers (Appendix 2.2) would also have been vulnerable to acid attack (Appendix 2.3).

2.3.11 Given the unknown quantity of particles likely to be trapped in the ODC and its related pipework, and the unambiguous indications that the integrity of the rocks above the roof of the ODC itself is suspect (see 2.3.12 below and Appendix 2.4), it is important to explore the possible causes of this lack of integrity, in order to foresee the problems that it will pose for decommissioning.

2.3.12 **Geology** The nature of the sedimentary rocks comprising the strata between the top of the ODC and the sea floor has been established (Fig. 2.8) by means of the rock cores from the borehole sunk as part of the site investigation for the construction of the adjacent ND. These cores have been examined by a geologist, Dr U. Michie, who has established the detailed stratigraphic sequence of the Middle Devonian rocks of the Dounreay area. (Michie 2006); his conclusions are endorsed by DPAG. The strata involved include facies A,B,C and D of the six facies identified by Michie (2006); of these lithofacies A and B are particularly susceptible to acid attack (see Appendix 2.4).

2.3.13 The borehole evidence (Fig. 2.8) has recently been supplemented by direct video camera observation of the whole of one of the unlined risers (riser 1) that link the sea bed with the soffit of the ODC. The conclusions reached from this direct inspection are consistent with the presence of abundant interconnective fissuring of the roof rocks of the ODC inferred from the observations of divers during dye-testing of the discharge system, reported on in 1981, 1983, 1997. The fissuring involved is interpreted as the result of nitric acid effluent (pH~2) attack on carbonate rock cements, especially in rocks of facies A and B and carbonate linings of faults and fault-related joints and fissures. Because the sediments dip at shallow angles from the horizontal (~10º) and both the faults and related joints that transect them are steep/vertical, the interconnectivity between fissured sedimentary layers and fissured fault rocks is easily understood, especially as the roof rocks had been rendered "sound" by cementitious grouting of all the extant planes of weakness in the rocks before the risers were drilled (Appendix 2.2). The vulnerability of such grouts to acid attack is discussed in Appendix 2.3.

2.3.14 The video record was complemented by a gamma detector that provided the gamma profile shown in Fig. 2.8. This shows a strong positive correlation with beds of the rock types having a calcareous cement, thus being most susceptible to acid attack. Further, the high gamma count between 11 m and 17 m below the sea floor (Fig. 2.8) coincides approximately with the zone from which the engineers, while constructing the OD system, encountered a "considerable influx of sea water", and which is characterised by numerous cracks observed on the video. It was this influx of sea water that that led the engineers to grout the whole volume of the roof rocks so comprehensively that the drilling of the risers posed no further problems from influxes of water (Shimmin 1963).

2.3.15 **Radiation and Salinity Surveys of the Seabed Above the ODC** On 31 May and 1 June 2007, divers conducted a survey of radioactivity and salinity on the seabed around the OD, unplugged one of the risers and inspected it by video camera. This section summarises the findings and discusses their implications. Detailed comment on the video recording of the riser appears as Appendix 2.5.

2.3.16 The survey of radioactivity used a NaI detector to record gamma activity, with detailed spectra being taken at selected locations. The results are described in detail in Howse (2007b). Several areas close to the OD with high gamma count rates were located (Fig. 2.10, modified from Howse 2007b, fig. 13). The lowest count rates found in this survey were around 100-200 cps (counts per second), and the areas highlighted in Fig. 2.10 all showed count rates that were at least several times greater than this. Several areas showed very high count rates, and very approximate locations of these are shown on Fig. 2.10. Especially notable are the following:

- Two areas W of the ND had count rates of ~7,000 and ~22,000 cps, both associated with rock step and gully features on the sea floor;
- Over the OD the general count rate is ~800 cps, but areas with rates up to ~20,000 and ~30,000 occur close to the NW face of the ND structure;
- Activities of ~900 cps were found at the foot of the NE face of the ND, associated with a fissure up to 25 mm wide that could be followed to a point 11 m from the ND;
- Activities of ~900 cps occurred in the rock wall of a sandy gully to the S of the ND;
- Several areas with very high count rates (~100,000, ~60,000 and ~100,000 respectively) were found along the rocky face of a sandy gully that lies NE of the OD. This gully face contains a horizontal fissure and the highest activities are associated with it. This fissure appears to be the same as one sketched by a diver involved in the 1980 dye tracing experiments. The sketch indicated “discharges” emerging from points distributed along the length of the fissure.

2.3.17 **Circumstances and mechanisms that caused the OD system to trap and release particles** Acid solutions have been pumped for several decades through man-made unlined vertical holes above the soffit of the ODC that cut through rock strata that dip at about 10º to the horizontal. The calciferous nature of the grout used to render the rocks impermeable to influxes of water, the natural carbonate cements in the rocks and probable occurrence of carbonate veining collectively made these rocks highly vulnerable to acid attack during discharges of acidic liquid wastes. The hydraulic head in the risers would have been greater than that in the surrounding rocks, so fluid will have tended to penetrate any cracks or fractures that were intersected. These planes of weakness tend to be bedding-parallel, shallowly inclined fissures, or fault/joint-parallel steeply inclined fissures (see Fig. 2.9 for an illustration of the potential for such intersection). If such a fissure occurred in material that was susceptible to acid attack, the walls of the fissure would have dissolved and the aperture would have been widened by the acidic fluids entering it from the riser. Continuation of this process would inevitably result in a series of interconnected fissures and/or channels through the rocks above the ODC. An assessment of the processes involved is given in Appendices 2.2 and 2.3.

2.3.18 In normal operation, only two of the nine-inch pipes were used. About 200 m^3 of effluent was discharged during one - two hours twice each day, providing peak flow rates of 14 - 28 litres per second and water velocities in each riser of ~1.5 ms^{-1}, during the period when the system was functioning as designed. The peak liquid velocities in the nine-inch pipes would have been about 0.65 ms^{-1}. These velocities would have been quite sufficient to carry sand grains and small rock fragments that may have been loosened by acid corrosion, and discharge them from the riser upstands onto the sea bed. Diver videos taken in 1996-7 show small mounds of rock particles around fissure openings adjacent to the ND. They were probably deposited by fluid emerging from the opening and slowing in velocity as it encountered and mixed with sea water.

2.3.19 Once fissures that connected with the sea bed had developed, the peak velocities in the upper parts of the risers would have declined as more of the discharge was diverted through channels in the surrounding rock. The rocks forming the ODC roof contain fissures which developed, at least partly, in the period between completion of the OD in 1958 and the diving inspections of 1981-3. It is probable that particles carried by the flow up the risers would have been swept into such fissures and came to rest there. It is also possible that the risers themselves contain sediment that contains particles, and that, with diminishing efficiency of the risers, as a result of acid attack during discharges of liquid effluent, sediment containing particles will have accumulated within the nine-inch pipes in the ODC itself. Some particles may have been discharged *via* holes in pipework into the Chamber and be resting on the Chamber floor, but see 2.3.23 below. Unless disturbed during decommissioning, most of these possible caches of particles do not pose a threat of wider contamination, although it is possible that particles trapped very close to the exits from fissures onto the sea bed could be dislodged by tidal currents or by fresh water discharges rising to the sea bed from the LEDT and ODC. Movement of substantial quantities of particles from fissures to the sea bed seems unlikely.

2.3.20 Radioactive particles that were discharged down the nine-inch pipelines could have entered fissures, could have been trapped, or could have discharged to the sea bed. Because a large number of radioactive particles were discharged *via* the LEDT from the early 1960s, it is likely that some remain trapped in fissures in the rock above the ODC. The number of such trapped particles is completely unknown.

2.3.21 Radioactive particles may also have escaped from damaged pipework into the ODC, but see 2.3.23 below. It was deduced from the evidence of the ROV inspection in 1989 (Appendix 2.1) that either there is a hole in at least one of the nine-inch pipes in the ODC or just outside the bulkhead wall, or that an open fissure has developed that links several risers to the ODC roof (Appendix 2.2). Whichever is correct, both of these situations could have resulted in the discharge of radioactive particles onto the floor of the ODC. Velocities of water within the ODC were probably not very high, even during effluent discharges, and sand-sized particles are likely to have come to rest on the chamber floor, perhaps against the walls or in corners. As with the possibility of particles being trapped in fissures, there are no real constraints on how many, if any, particles are present.

2.3.22 There is a possibility that particles may have collected at times as a shoal along the nine-inch pipes. When the system was operating normally, velocities in these pipes would have been 0.3 to 0.65 ms^{-1}, which is quite adequate to keep sand and small gravel grains in movement. However, shoaling is a possibility in that part of the nine-inch pipe that acted as a manifold, to which the smaller pipes were attached. Photographs (*e.g.* Fig. 2.5) show that two of the nine-inch pipes had riser pipes joined to their top surfaces, and particles may have shoaled beneath these. In particular, at the far end of these nine-inch pipes, local velocities would have been below 0.16 ms^{-1}, and shoaling may have occurred here. If shoals of sand or gravel-sized particles are present within the nine-inch pipes, radioactive fuel particles may also be present among them. If shoaling had become severe, then some radioactive particles might be present within the pipes in the LEDT to landward of the bulkhead door of the ODC; however, the ROV radiation detector gave no alarm in this area, although the vehicle was within a metre of the pipes.

2.3.23 On 2nd-3rd June 2008 a video inspection of riser 1 that penetrated into the ODC (Fig.2-11) provided the following information:

a) The now-fissured nature of the originally smooth walls of the riser. There are large numbers of fissures in the top 5 m, but below this level the rocks seem to be mainly smooth with less frequent fissures;

b) On the initial removal of the plug from the sea floor, dark particulate matter issued vigorously onto the sea bed, above the ODC. The liquid which issued was like rusty water, any particulate matter being fairly buoyant;

c) Strong vortexing of water streaming upwards in the riser and some turbulence of water within the ODC, both probably driven by both groundwater flow and by tidal forces. The vortexing was caused by flow through pinholes in pipework, while the rate of flow in both the ODC and the riser was limited;

d) Although not quantified, the low salinity in the waters encountered indicates that the main contributor is groundwater;

e) The possible extent of the frailty and brittleness of at least some of the pipework within the ODC became apparent when a section detached and fell, possibly as a consequence of the intrusion of the video camera;

f) The existence of an estimated 200 mm of fine sediment on the floor of the ODC;

g) Lack of evidence for high levels of radioactivity within the ODC.

2.3.24 On the basis of the video, as discussed in 2.3.23 above, we suggest that:

a) The pipework in riser 1 was essentially intact prior to this inspection, although perforated and this may imply that the pipework was intact twenty years ago and hence, during the period of major particle discharge, their release would have been to the risers/rock mass, and not to the ODC;

b) The presence of sediment on the floor of the ODC is not a surprise if the grout used to hold the roof liners in place has been dissolved.

2.4 Conclusions

2.4.1 Particles are likely to be encountered onshore during the decommissioning of:

- at least one location (the DMTR Complex) in the Non-Active drainage system;
- the old Low Active Drainage System – now encased in concrete;
- two sections of the New LAD close to the DMTR;
- the Sea Tanks;
- the Wet Silo;
- the seven on-site LLW pits;
- Landfill 42;
- the Shaft (now isolated).

It is also possible, but considered highly unlikely, that small particles are present in the rock mass to the N and W of the Shaft, having been already in transit before Shaft isolation work began in 2006.

2.4.2 Apart from particles already on the sea bed and adjacent beaches, particles are likely to be present offshore in three locations related to the OD:

- within pipework in both the ODC and the LEDT;
- in the unlined sections of the risers as well as in fissures within the rock mass between the ODC and the sea bed;
- in the ODC itself.

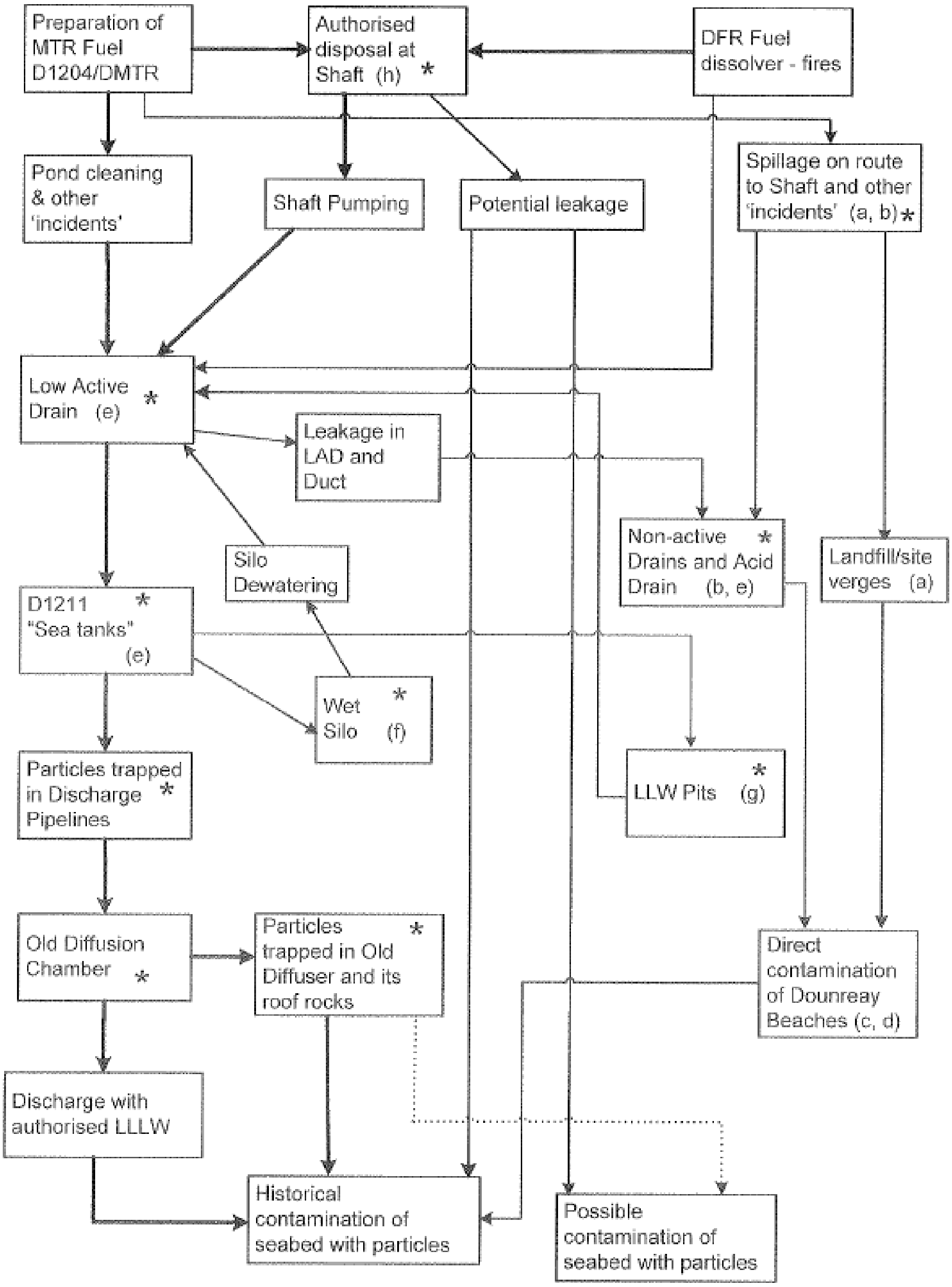


Fig. 2.1 **Liquid Discharge Routes for Particles (adapted from DPAG 2006, fig. 2.2, p. 19) * Indicates potential sites retaining particles; a-h refer to localities identified in the text**

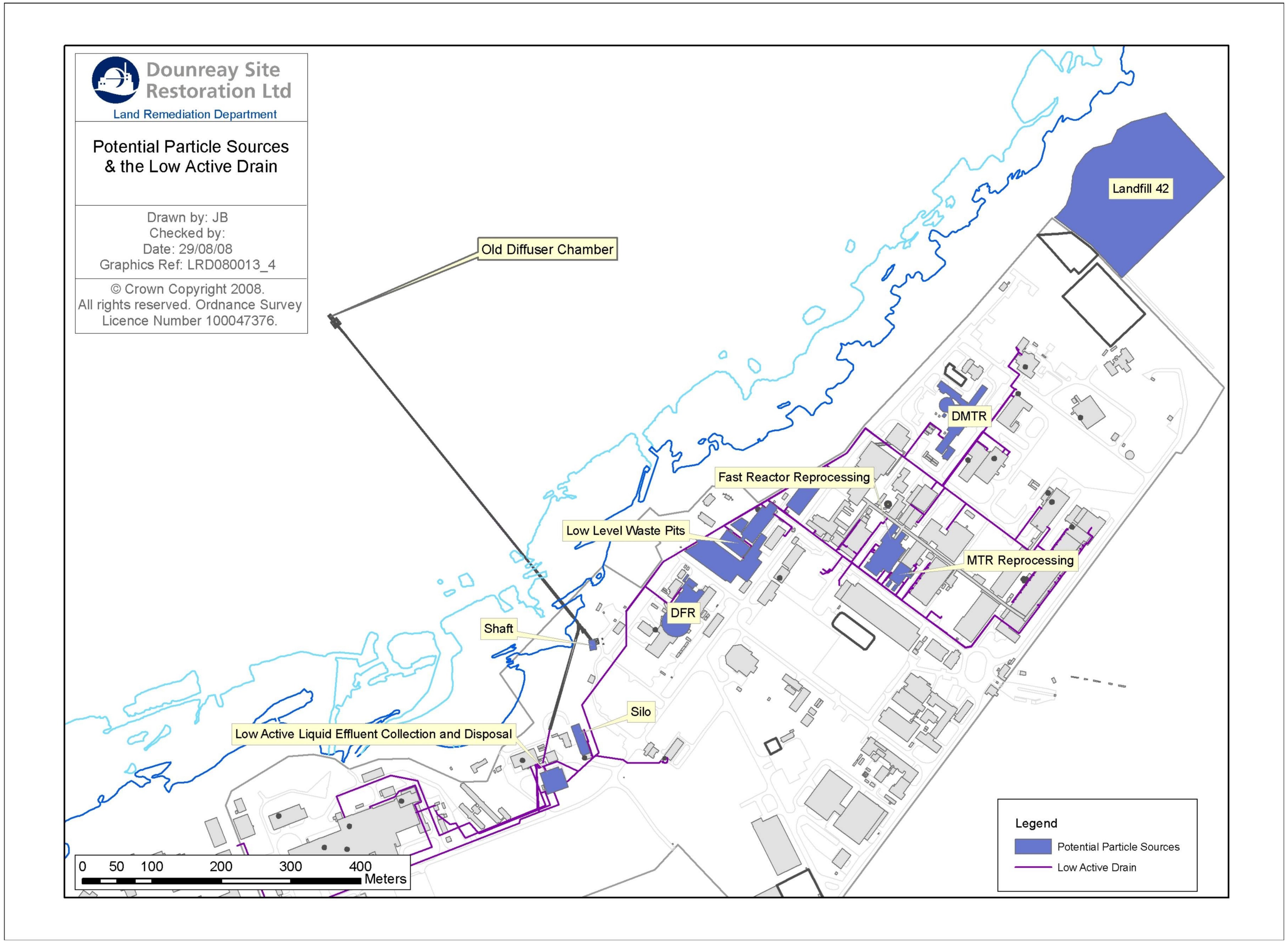


Fig. 2.2 Map Showing the installations on the Dounreay Site and the route of the Low Activity Drain

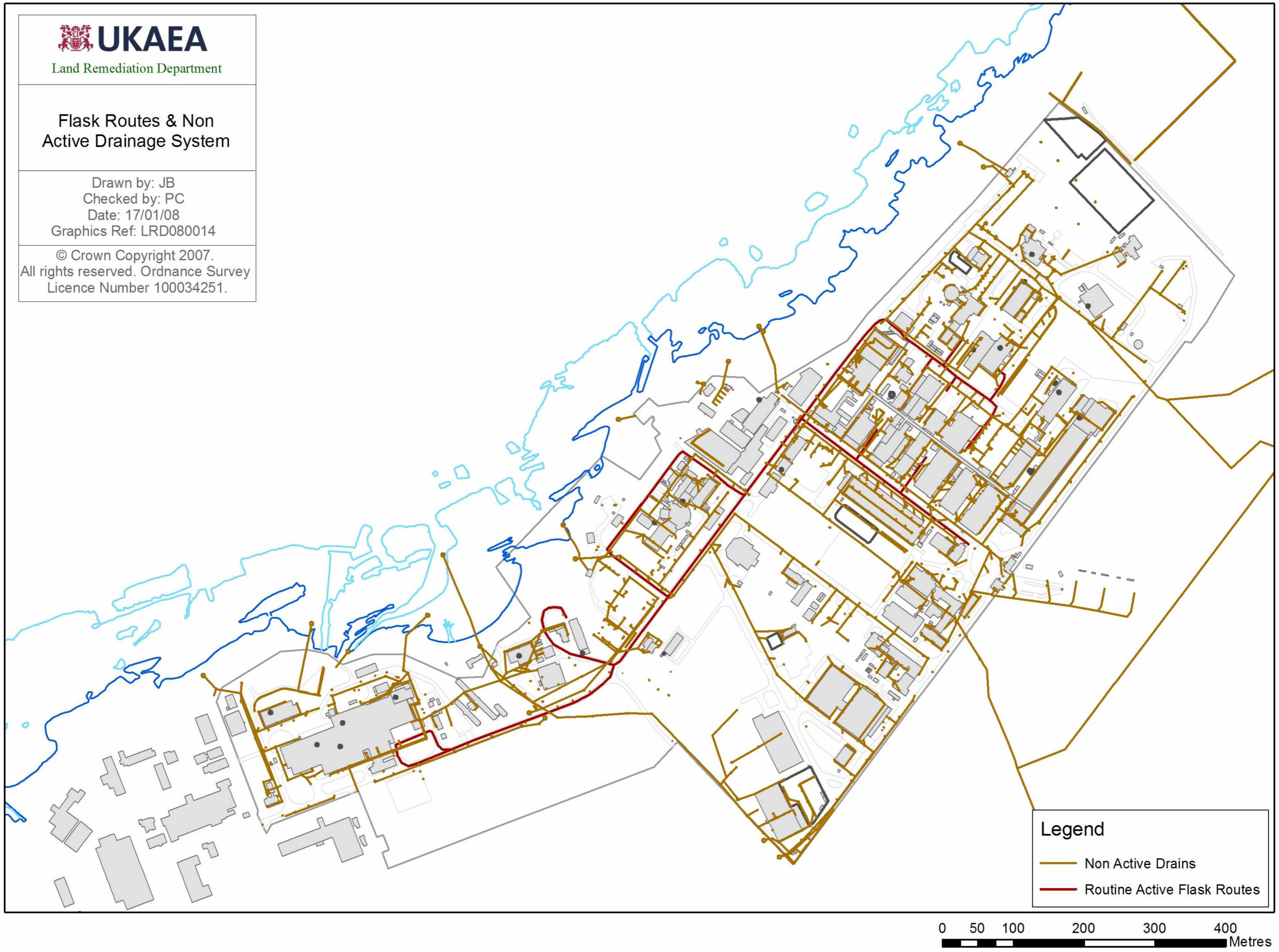


Fig. 2.3 **Map showing the route of the Non-Active Drains and the routes followed on site by flasks conveying swarf derived from reprocessing activities**

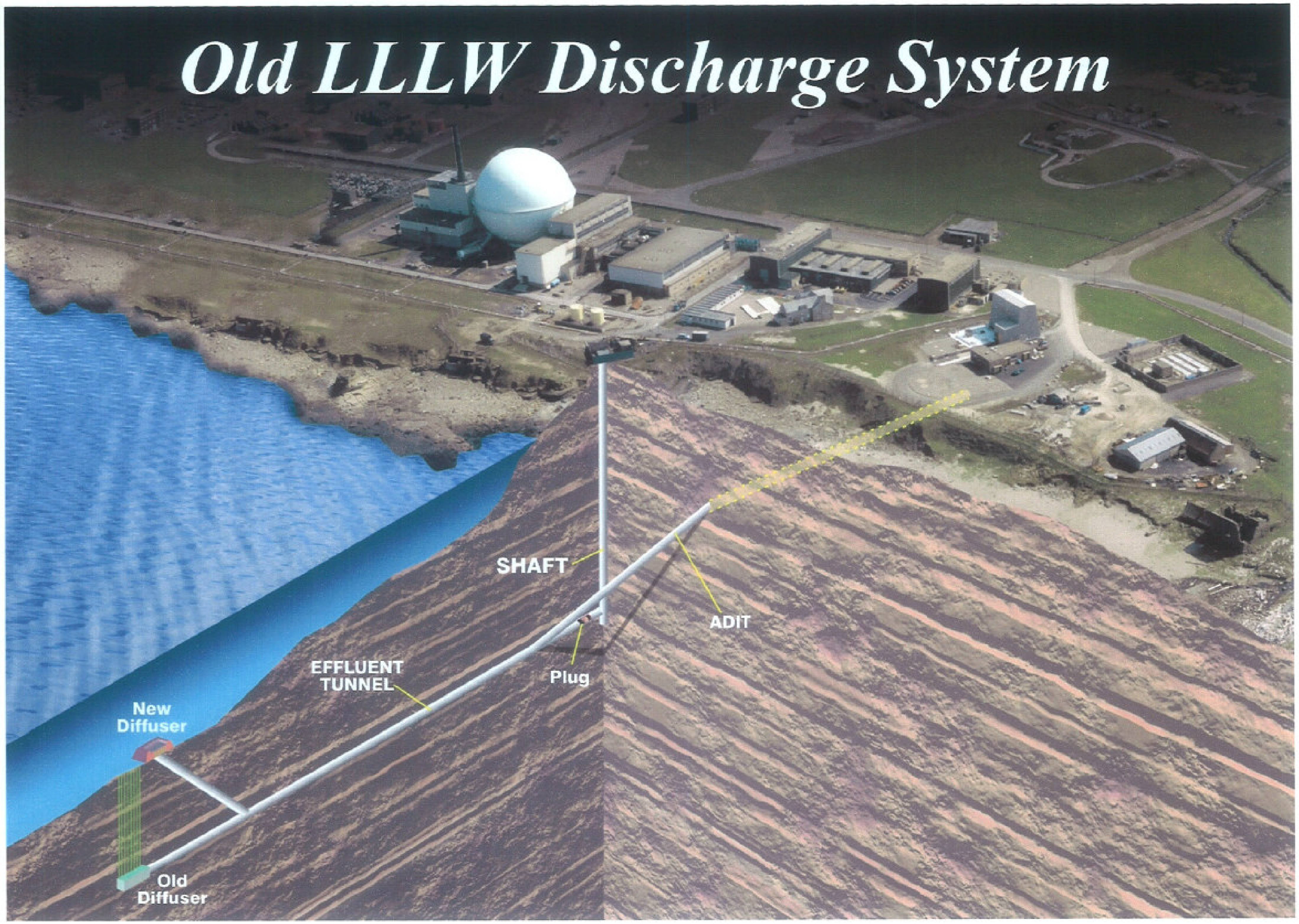


Fig. 2.4 Cut- away 3D section through Adit, Shaft, LEDT showing the configuration of offshore installations and their links to the onshore Dounreay Establishment

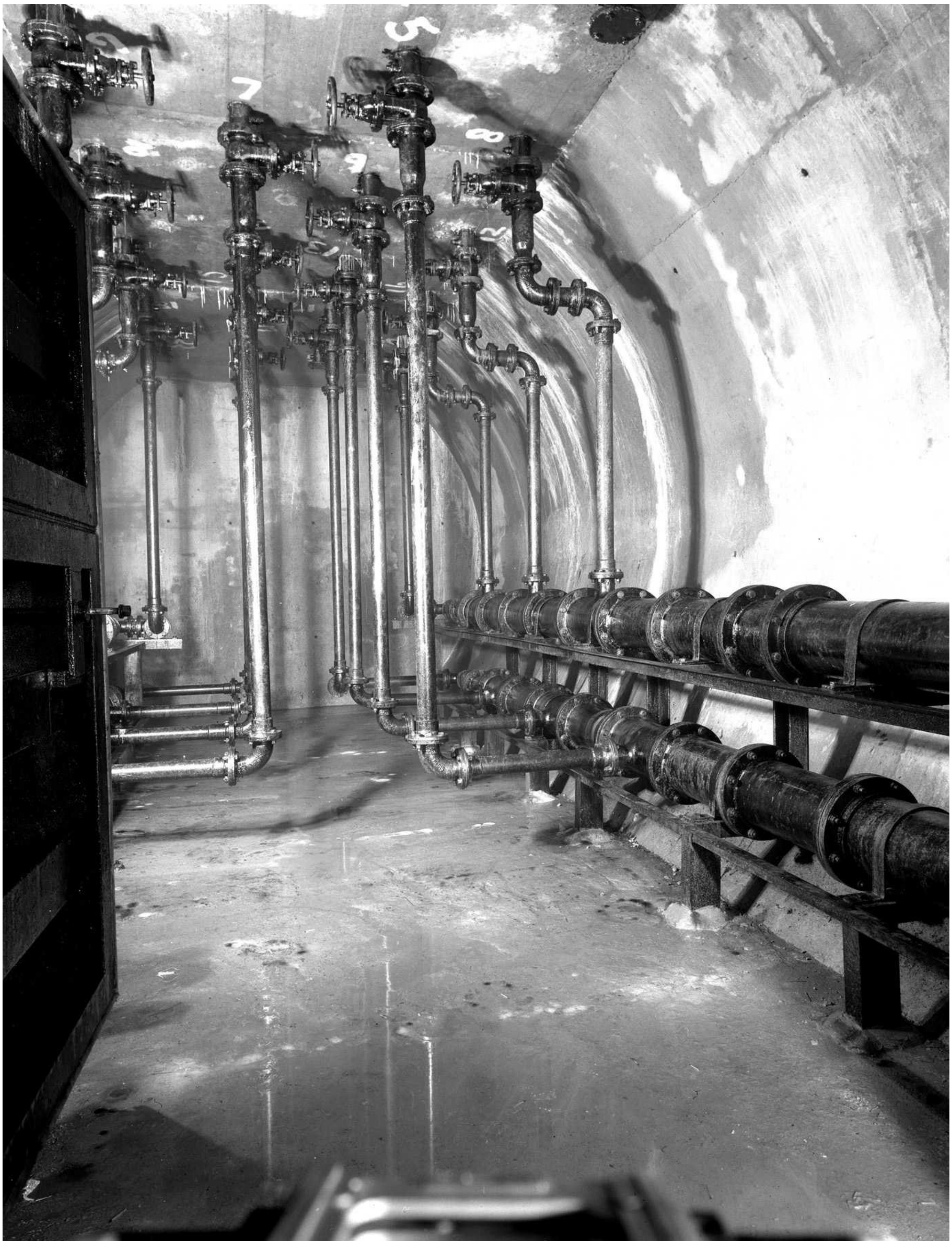
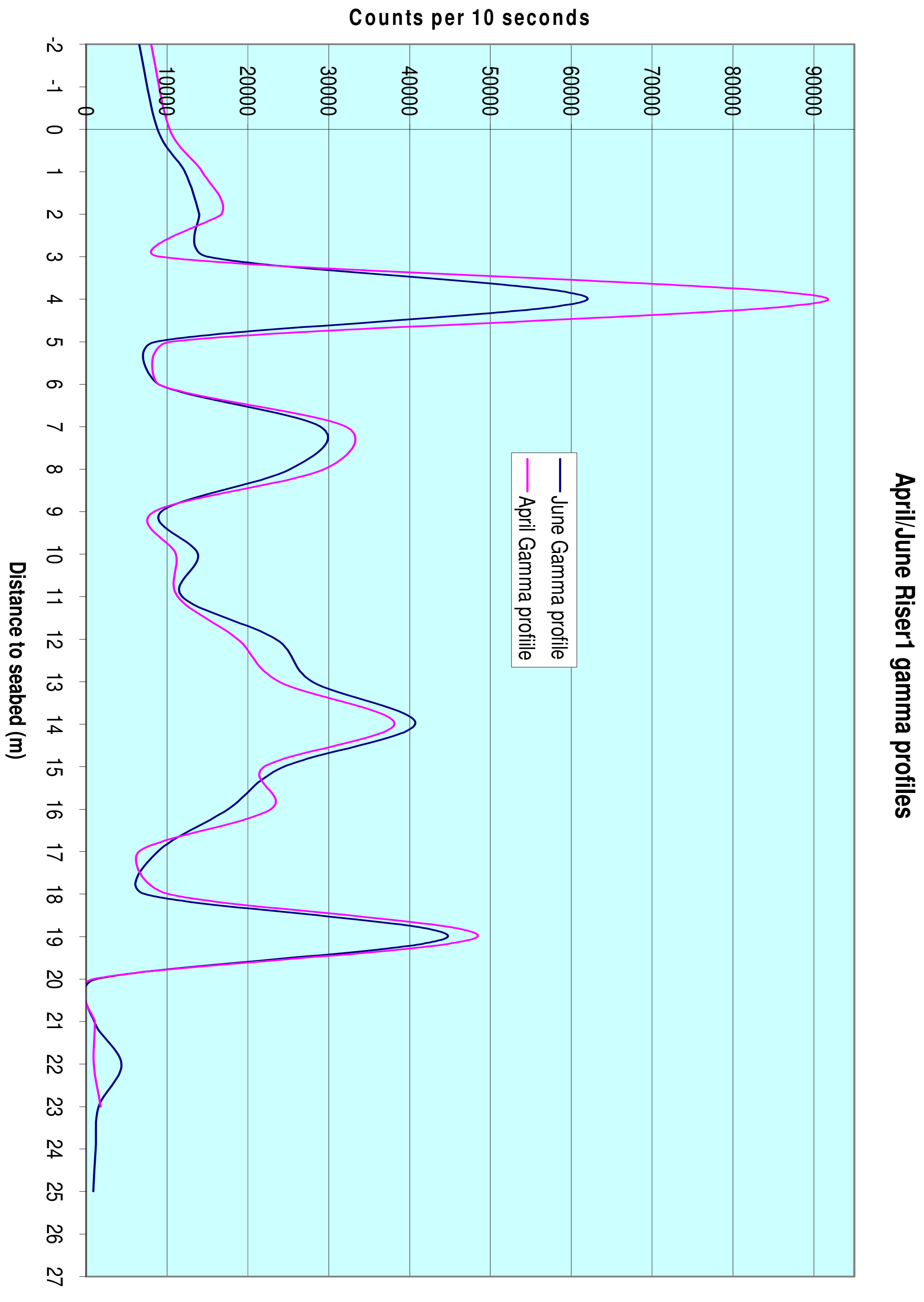


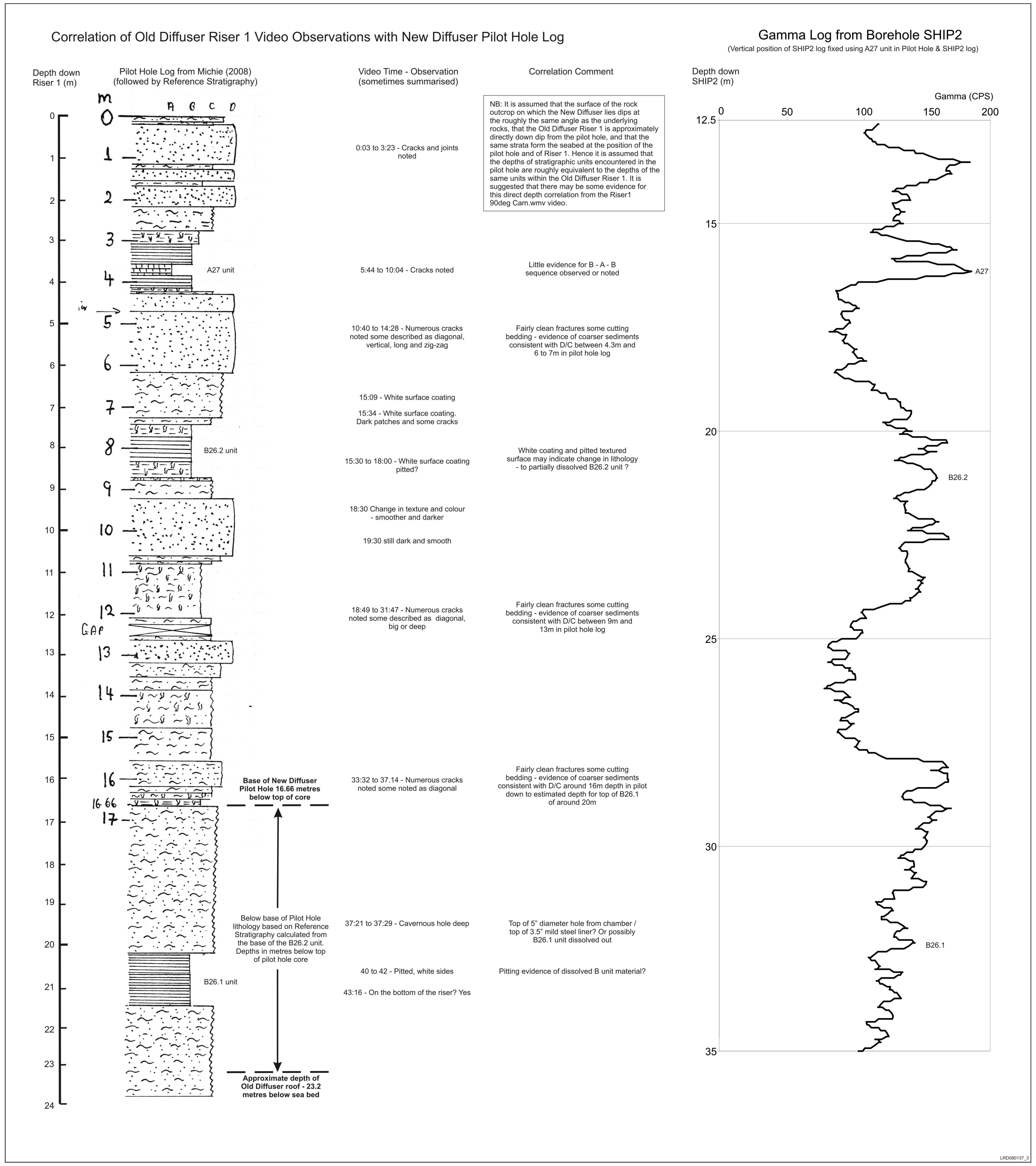
Fig. 2.5 Viewed from the door of the ODC, two of the horizontal nine-inch pipes with risers attached, leading up to the roof of the ODC

Fig. 2.6 Photograph of the door of the ODC , viewed from within the ODC, and showing the two pairs of nine-inch pipes, prior to the installations of the risers

Fig. 2.7 Concrete haunch in the LEDT containing the four liquid effluent pipes



Plot of the April/June gamma profile surveys of Riser1.



Interpretation of information from rock cores taken during the 1992 Penrod64 pilot hole drilling. [U Michie, April 2008; J Bonniface May 2008].

Fig. 2.8 **Geological section down riser 1, passing through the roof rocks above the ODC, showing the correlation between calcium-carbonate bearing rocks/grouted rocks and zones of enhanced radioactivity**

Fig. 2.9 Photograph at an unknown locality within the LEDT to demonstrate the relationship between the shallowly dipping (bedding) planes intersecting the steeply dipping (joint) planes that are related to faulting

Figure 2.10 shows an approximate composite of all of the areas where radioactivity was surveyed for (blue) and detected (pink) on the seabed around the diffusers.

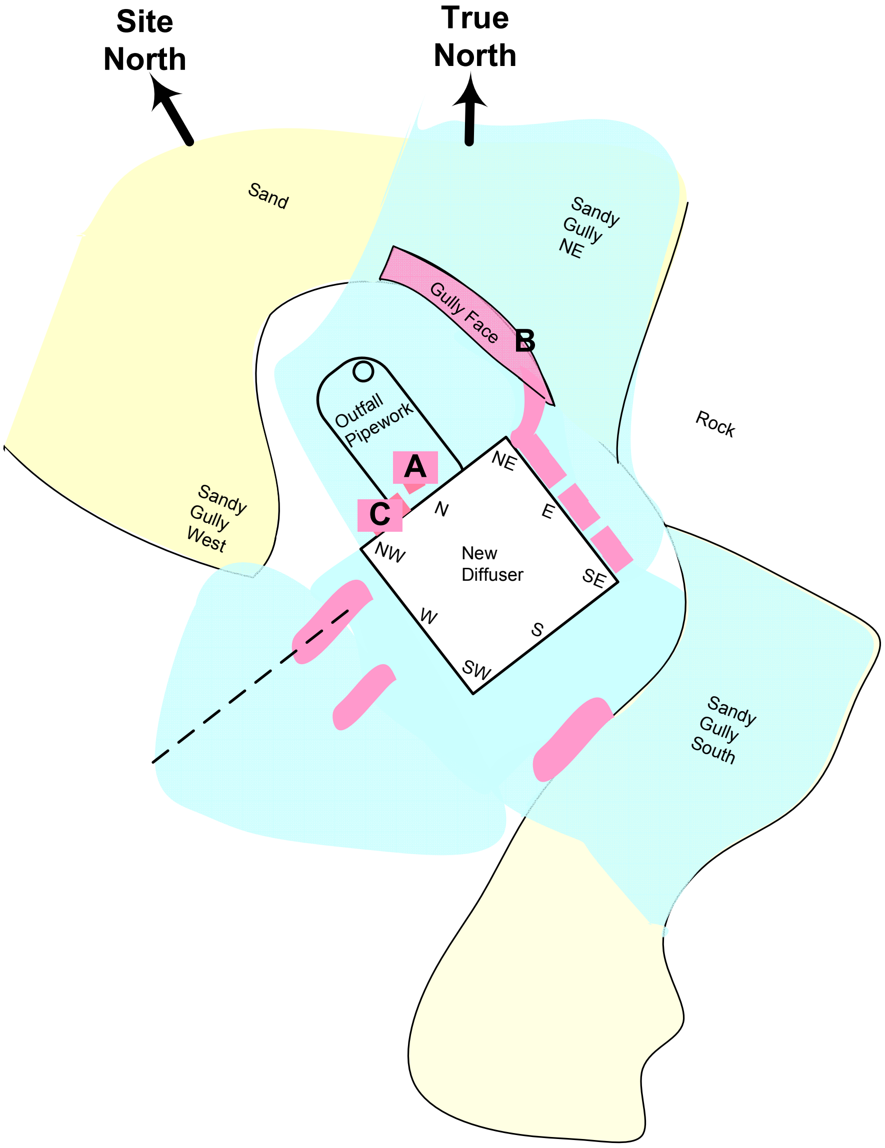


Fig. 2.10 Approximate areas of radioactivity in relation to the diffusers

Positions A, B and C refer to elevated radioactivity regions above Riser 1, on the gulley face and next to the foot of the north wall of the new diffuser respectively

Note that it has been a site convention to refer to 'North' as being Dounreay 'Site North'. 'Site North' is approximately 45 degrees west of 'True North'. This convention has been applied throughout dive and survey documents and video recording logs for many years. This fact should be recognised when reviewing current and previous diffuser related documents.

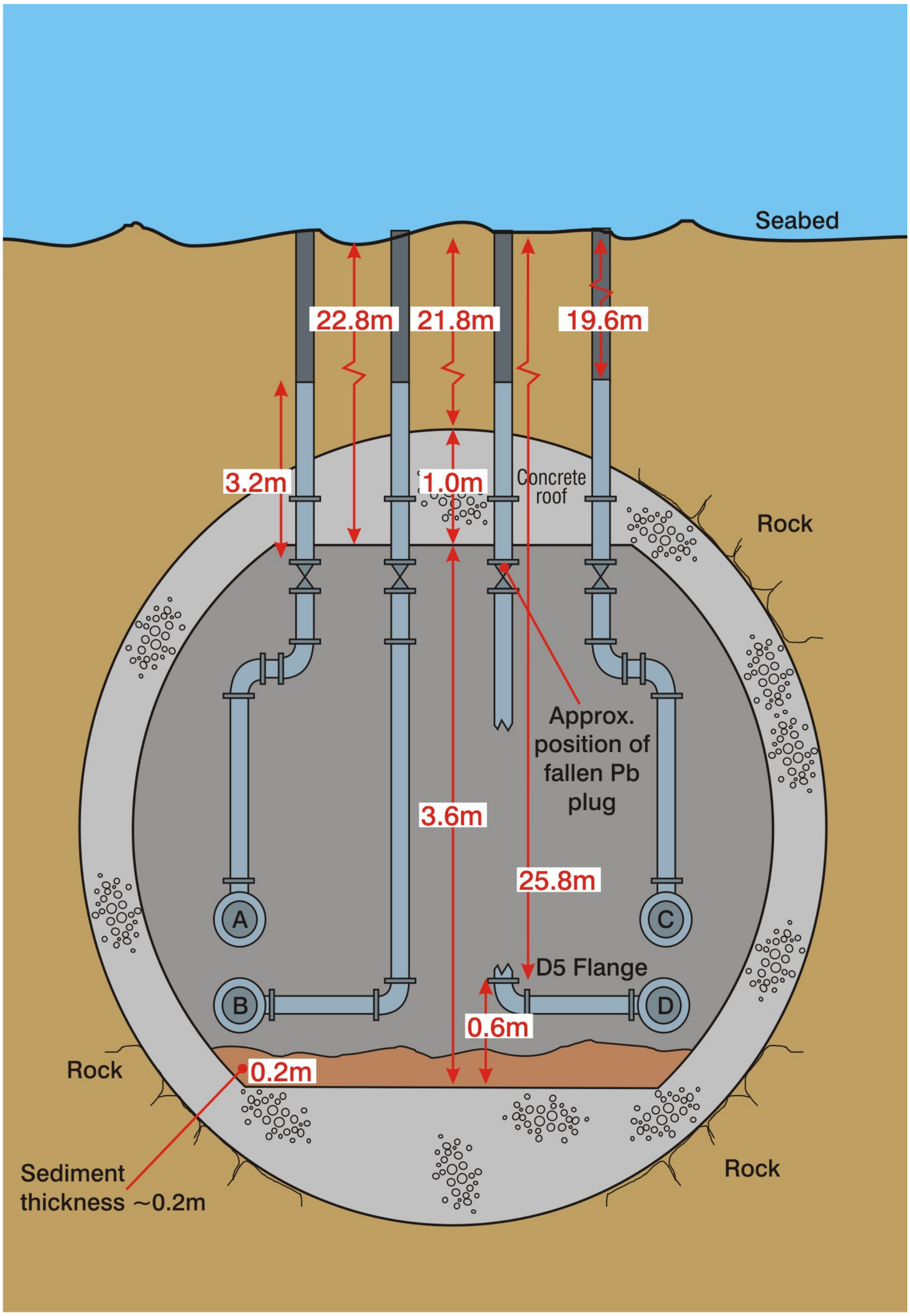


Fig. 2.11 **Diagram showing conditions in the ODC inferred from the video inspections of June 2nd and 3rd 2008**

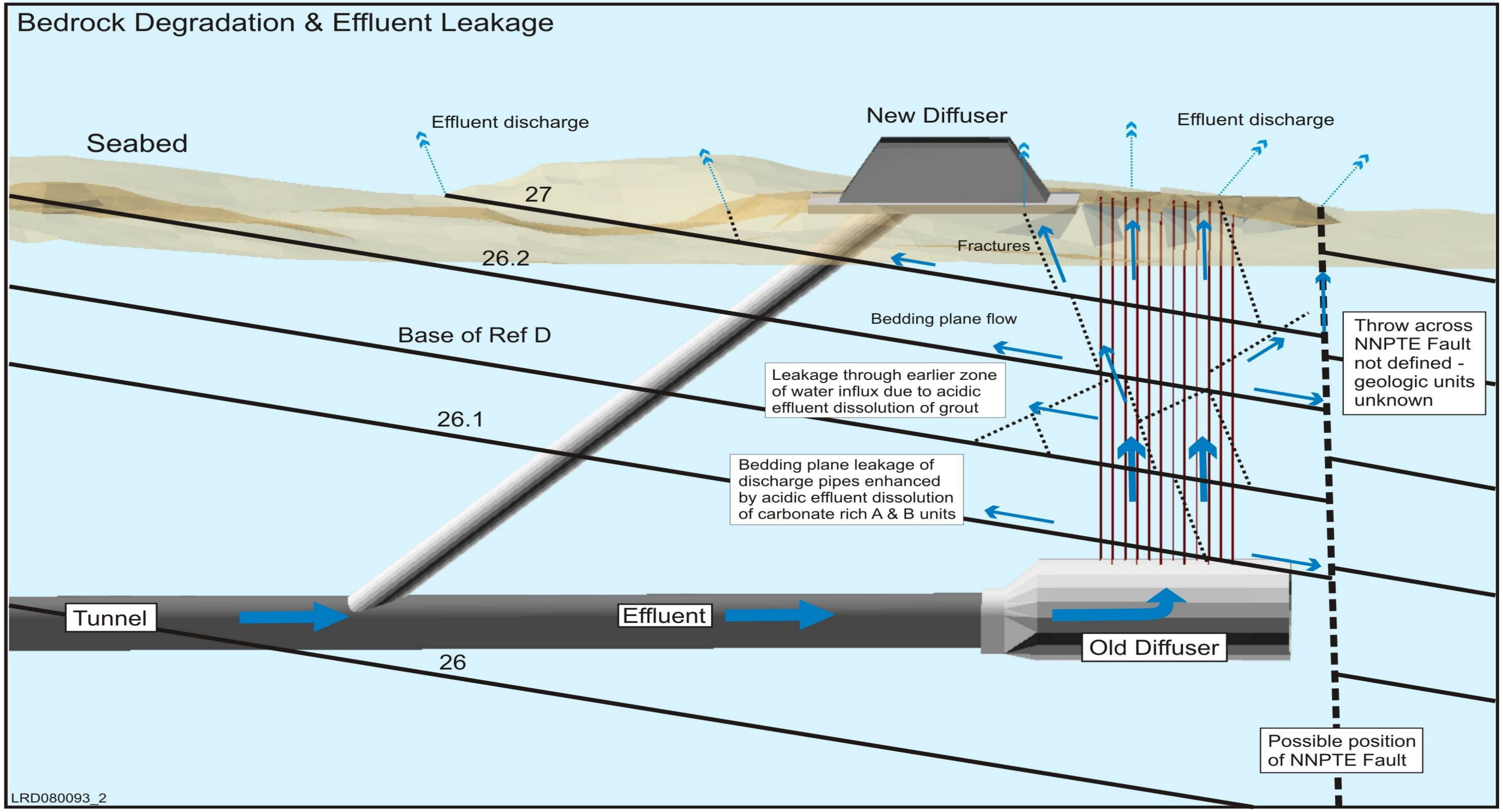


Fig. 2.12 Bedrock degradation

3. Further Studies of Particle Characteristics

3.1 Density

Introduction

3.1.1 The distribution of particles in the marine and intertidal environment is determined by their physical attributes in terms of shape, size and density rather than their chemical characteristics. In our Third Report[2] (DPAG 2006) we noted that 'the density of Dounreay particles, although a critical property controlling transport and deposition, has proved frustratingly difficult to establish through measurement'. Furthermore, shape, size and density 'are known very imperfectly and only for sub-sets of particles which were selected on arbitrary grounds and so do not necessarily constitute a representative sample of either the recovered particles or the overall population in the environment'[3]. At that time, no measurements had been made on DFR particles. DPAG went on to recommend[4] that:

- a larger sample of the particles recovered should be characterised to determine their mass, density, shape, size, composition, chemical reactivity and radionuclide content to test assumptions made as to the behaviour of particles in the sea;
- UKAEA carried out measurements of density on both MTR and DFR particles using a flotation technique as described below.

Methodology

3.1.2 Thirteen MTR particles and four DFR particles were measured. Estimates of particle density were determined by observing whether the particle sank or floated in solutions of sodium polytungstate (SPT) of known density. A series of aqueous solutions of SPT was prepared to provide solutions of known density of approximately 2.6, 2.8 and 3.0. Individual particles were then placed in the solution and the sample centrifuged. The density was then determined as either greater or less than that of the solution according to whether the particle sank or rose in the solution.

Results

3.1.3 The results for all the particles are provided in Toole (2007a). Particles showed a density range of between about 2.7-3.1 g cm^{-3} for the MTR particles. The results are shown graphically in Fig. 3.1 which shows densities of MTR

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[2] Paragraph 4.2.16, page 47.

[3] Paragraph 4.2.18, page 48.

[4] Recommendation 7.8.4, page 148.

particles arranged by location and ^{137}Cs activity. However, it is notable, as shown in Fig 3.1, that there were two particles with greater densities. The range is similar to that predicted for MTR particles based on fuel composition and uranium content. In theory the density of non-porous particles comprising aluminium-uranium alloy should be in the range of 3.0-3.4 g cm^{-3} depending on the uranium content. The density of pure aluminium is 2.75 g cm^{-3}. It was therefore assumed in our Third Report (DPAG 2006) that the density range was 2.7-3.4 g cm^{-3}.

3.1.4 The density of all four DFR particles was determined to be greater than 3.1 g cm^{-3}. Toole (2007a) postulate that the relatively high density reflects the density of the main elemental constituents, uranium, niobium and iron.

3.1.5 The results obtained using the SPT method were compared with those obtained using computer aided analysis of photomicrographs for four MTR particles. As illustrated in Fig. 3.2, the results show a poor agreement. Toole (2007a) consider that the SPT technique is more reliable and recommended that any further measurements should be made using this technique.

Discussion

3.1.6 UKAEA's original approach to measuring density was to construct 3-D images of particles through microscope photography from different angles, with estimation of volume by a computer algorithm which performs a 3-D triangulation (referred to hereafter as the CAD method). As reported in our Third Report (DPAG 2006), this method was piloted on nine particles only three of which had calculated densities within the predicted range. The other six had much lower densities probably because of their irregular shape. The method was not tried on DFR particles because it was considered that their porosity would inevitably result in an underestimate of their density. The SPT method does appear to show greater accuracy for MTR particles. The impact of irregular shape on the CAD method is the most likely explanation for the variation observed.

3.1.7 The applicability of the SPT method for DFR particles is less satisfactory, however, because these particles do not fall within the density range that can be readily prepared using SPT solutions. Higher density solutions up to 4.0 g cm^{-3} could be prepared by the addition of tungsten carbide powder but UKAEA is concerned that it might not be possible easily to retrieve the particles from the mixture. Furthermore, there is some uncertainty over the measurements of the four DFR particles because it is not known to what extent the measurements were affected, if at all, by the presence of pores. Consequently, Toole (2007a) referred to the DFR results as 'apparent densities'.

3.1.8 From Fig. 3.1, it is possible to identify particles according to where they were found. There was no evidence of a statistically significant difference between the density of particles from different points of retrieval based on this very small number of sampled particles.

3.1.9 It is not possible from these results to correlate density with activity. The more uranium in the fuel fragment, the more fission products and hence the greater the ^{137}Cs activity. In theory, therefore, one might expect that the more active particles would have a higher density. This would be an important characteristic, given the influence of density on transport and deposition and might offer an explanation for the lack of *significant* particles on Sandside Beach. However, as Toole (2007a) noted, there are confounding factors. First, the ratio between uranium and aluminium in particles is not constant and secondly, the amount of fission product of the ^{235}U present will depend on irradiation history – although it has been suggested by UKAEA that these differences will not be great because fuel elements were removed from the reactor at specified burn up of the ^{235}U component - but more importantly, the position on the fuel element from which the particle arose.

3.1.10 DPAG concludes that, while the SPT method offers a means of determining the approximate density of MTR particles, there is probably little more to be gained by taking further measurements. Because particles of the same density may be of different size, shape and activity, they may behave differently in the environment.

3.2 Solubility in Acid Conditions

Introduction

3.2.1 As reported in our Third Report (DPAG 2006)[5], the results of *in vitro* experiments to evaluate the potential solubility of particle-associated radionuclides in the gut showed that, while most particles exhibited low solubility, one particle, MTR 113, dissolved readily and about 50% of the activity went into solution in simulated gut fluids. DPAG was informed that a possible explanation for this exceptional behaviour was that the particle comprised uranium oxide rather than the usual uranium-aluminium alloy. It was noted that about 900 experimental MTR fuel elements, some of which did not contain uranium-aluminium alloy, had been reprocessed to the end of 1973. Some of these were believed to have contained uranium oxide (U_3O_8)-aluminium alloy plates. It was suggested that less than 1% of the elements reprocessed did not contain uranium-aluminium alloy so that the number of particles generated and subsequently discharged was proportionately smaller[6]. However, given the health implications of ingesting a particle that readily dissolved in gut fluids, DPAG recommended[7] that:

- Work be undertaken to establish a best estimate of the proportion of particles of similar characteristics to particle MTR 113 that may have been released.

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[5] Paragraph 3.1.8, page 25.

[6] Paragraph 2.1.14-18, page 8.

[7] Recommendation 7.8.7, page 148.

Methodology

3.2.2 Tests were carried out on 151 particles out of a list of 160 particles randomly selected by DPAG, the remaining particles being retained as a contingency. Of these 160 particles, 132 came from the sea bed, ten from Sandside Beach and eighteen from the Dounreay Foreshore, roughly reflecting the distribution of finds from each location.

3.2.3 The dissolution characteristics of these particles were tested at 37°C using hydrochloric acid at pH2 as a reagent. The experimental protocol was agreed between DPAG and UKAEA and further details are available in Hall D.T. *et al.* (2007). All sample filtrates were assayed using gamma-ray spectrometry and Inductively Coupled Plasma Mass Spectrometry (ICPMS) was used to quantify amounts of aluminium, uranium and cobalt released into solution. Filters bearing the solid residues were subjected to gamma-ray spectrometry.

Results

3.2.4 Samples were tested in fifteen batches. The experimental protocol for the first batch was slightly different but UKAEA considers that the differences would not have had a large effect on the results compared with those of the other samples. The results from this first batch have therefore been included in the data set.

3.2.5 As shown in Fig. 3.3, most particles showed losses of ^{137}Cs in the filtrate of less than 4%. For three of the particles, however, there was apparently a much higher percentage, as indicated in Table 3.1.

3.2.6 Fig. 3.4 shows the quantity of uranium found in the filtrate samples against the activity of the particles as measured shortly after retrieval. The Figure also shows the calculated amount of uranium which would be expected in uranium oxide particles for two different densities of U_3O_8 based on information obtained from a single confirmed uranium oxide particle. Details of the calculations are included in Hall D.T. *et al.* (2007). UKAEA noted that ‘only five particles, all *minor*, show significant amounts of uranium dissolution relative to the amounts calculated for U_3O_8 particles’.

3.2.7 Table 3.1, taken from Hall D.T. *et al.* (2007) summarises UKAEA’s observations on the seven apparently anomalous particles. All of these are *minor* particles. None of the *relevant* or *significant* particles showed elevated levels of dissolution or high amounts of uranium loss. Furthermore, of the seven anomalous particles, none was anomalous in respect of both criteria measured. The results led Hall D.T. *et al.* (2007) to conclude that ‘there is no persuasive evidence for the presence of uranium oxide particles in the 151 samples tested’.

3.2.8 Some explanations for the anomalous results are offered. Particle 982394, retrieved from the Dounreay Foreshore, showed an apparent 53% loss of ^{137}Cs to solution. However, when the activity balance between original activity and the sum of activities in the filtrate and in the solid residue are compared, the particle appears to show a large gain of ^{137}Cs. UKAEA suspect that this is because the original result was too low. The other two particles showed relatively high percentage losses of ^{137}Cs to solution but the actual losses were very small and there was no measurable uranium loss.

Table 3.1 Seven particles which yielded anomalous results in leaching experiments

Sample	^{137}Cs Activity in Particle (Bq)	% Loss ^{137}Cs to Filtrate	Loss of U to Filtrate (µg)	Loss of U to Filtrate (% of Total if U_3O_8)	Comments and Conclusions
02/085	1.3x10^3	75	<0.06	<13	Similar and low amounts of ^{137}Cs in filtrate, filter and original particle; no measurable U loss; such very small particles could show artefacts on U or Cs loss due to high surface area; volume ratios or shape; not U oxide particle.
982394	1.3x10^4	53	0.54	6 – 12	SEM-EDAX show it is an MTR particle; original reported particle ^{137}Cs result much too low so % Cs loss is an artefact of this.
05/097	2.5x10^4	8.96	<0.06	<0.6	No measurable U loss, low Cs loss; not U oxide particle.
04/030	1.7x10^3	0.54	1.56	130 – 270	Suggests total dissolution of U but negligible ^{137}Cs release; such very small particles could show artefacts on U or Cs loss due to high surface area; volume ratios or shape; probably not U oxide particle.
03/060	4.5x10^3	0.13	0.42	14 – 28	Low Cs loss, minor U loss; such very small particles could show artefacts on U or Cs loss due to high surface area; volume ratios or shape; probably not U oxide particle.
01/134	2.3 E+03	0.71	0.40	25 – 50	Low Cs loss, some U loss; such very small particles could show artefacts on U or Cs loss due to high surface area; volume ratios or shape; probably not U oxide particle.
04/053	2.2x10^3	0.15	0.36	24 – 48	Very low Cs loss, significant U loss; such very small particles could show artefacts on U or Cs loss due to high surface area; volume ratios or shape; probably not U oxide particle.

Discussion

3.2.9 The possibility that the unusual results obtained for MTR particle 113 in *in vitro* experiments commissioned by SEPA and reported by HPA-RPD (Harrison *et al.* 2005) could be due to its being a uranium oxide particle was not raised until just before the completion of our Third Report (DPAG 2006). The only information on the likely prevalence of uranium oxide particles was that deduced from the *in vitro* studies that found one unusual particle out of 23 (Harrison *et al.* 2005) and from the results of UKAEA analyses of some particles by energy dispersive X-ray analysis (SEM-EDAX) which found one unusual particle out of 186.

3.2.10 DPAG's purpose in making the recommendation for further studies was to obtain more information on the likely prevalence of particles that would be readily soluble in gut fluids. It was assumed, on the basis of information from UKAEA, that any such particles would be uranium oxide particles. The results of this study suggest that none of the 151 particles tested was uranium oxide, a result consistent with the previous observations. Only two uranium oxide particles have been identified, one confirmed by UKAEA during SEM-EDAX analysis and one inferred from the results of the *in vitro* experiments referred to above.

3.2.11 However, although none of the *relevant* or *significant* particles dissolved to any extent in the acid, a small number of *minor* particles did. The pattern of ^{137}Cs loss and uranium concentration levels for each of these suggests that these particles were not uranium oxide particles. In terms of impact on human health, however, it is the solubility that is of importance not the precise makeup of the particle. As shown in Table 3.1, the three highest reported percentage loss of ^{137}Cs to the filtrate were 8.96%, 53% and 75%. Even allowing for errors in measurement, these solubilities could be of significance. However, it is also worth noting that the percentage loss of ^{90}Sr to the filtrate is low. This is an important observation because, for soluble particles, this radionuclide would be an important contributor to the effective dose (Harrison *et al*. 2005). The implications of these results are discussed further in Chapter 7.

3.2.12 The result obtained for particle 982394 indicates that the gamma-ray spectrometry measurements carried out previously may not always provide accurate results, perhaps because of the counting geometry used at the time. DPAG is concerned that this result may be symptomatic of a larger problem, raising uncertainties over the reliability of other measurements. It suggests that, if possible, the activity of particle 982394 should be re-assessed by further analysis.

3.2.13 DPAG agrees with UKAEA's conclusion that the incidence of particles likely to dissolve on ingestion is very low.

3.3 Transfer of Radioactivity to Surrounding Sediment

Introduction

3.3.1 The collation of data on the discovery and retrieval of particles from Sandside Beach provides only limited information on which to base any hypothesis on the movement of particles on and off the beach, their movements within the beach and their overall residence times. Better information on these characteristics would be useful in designing future monitoring programmes.

3.3.2 In our Third Report (DPAG 2006), DPAG recommended that an evaluation of particle finds at Sandside in relation to beach height should be completed within about twelve months. UKAEA accordingly carried out a comparison of beach height profiles with finds of radioactive particles on Sandside Beach and drew conclusions as to whether particles finds were historic particles (H) revealed through beach erosion or recent arrivals (R) (Scirea, M. 2007a and 2007b). As a further way of testing these deductions, it was decided to analyse data on these particles to determine whether those identified as historic had contaminated the surrounding sediment more than those particles that had recently arrived.

Discussion

3.3.3 There are few clues as to the residence time of particles on the beach at Sandside. Tidal movements are likely to transport particles left on the surface but, without a detailed study of the sediment dynamics of the beach, it is not possible to predict how much they might be expected to move. It is clear from measurements of beach height, however, that there can be considerable movements of beach sediment in a single tide during stormy weather although it is not clear whether and if so how much of the eroded sand subsequently contributes to beach accretion. Given the lack of knowledge of the beach-sediment dynamics, it is difficult to postulate the behaviour of radioactive particles once they are deposited on Sandside Beach. The behaviour of particles is further complicated by bioturbation (Appendix 3-1) brought about by infauna. Sandside Beach has a population of lugworms *Arenicola marina,* a species that is known to draw surface sediment down into its burrow. As a consequence of these variables, it is difficult to draw any conclusions about how long a particle has been on the beach even if the precise site at which it was found has recently been monitored.

3.3.4 As an adjunct to the analysis of field data, UKAEA commissioned laboratory studies into the loss of radioactivity from particles into surrounding sediment. These involved placing particles in undisturbed, clean sediment for periods of up to six months. The work demonstrated that passive diffusion into the surrounding sediment and pore water did occur, and that the losses arose *via* radionuclides in solution rather than *via* fragmentation (Warwick and Croudace 2006, Toole and Parsons 2008). Rates of loss from the physically smaller *relevant* particles were not significantly different from the larger *significant* particles. The sample size was very small, however, and these results may relate to heterogeneity within particles and their shape, rather than their physical size. The diffusion mechanisms involved are not fully understood but UKAEA has concluded that, if the observed rates of diffusion were maintained, over a period of 30 years this process alone would reduce the activity of ^{137}Cs in a particle by about 19%. In our Third Report (DPAG 2006), we concluded that fragmentation would occur with a mean lifetime between events of between six and seven years, and that typically the largest fragment would contain about 80% of the original activity. On this basis, the diffusion process would be only a small contributor to the overall decrease in the activity of particles in the environment.

3.3.5 On the basis of the laboratory studies, it might be expected that historic particles would be associated with higher levels of contamination in sand than would particles that had only recently arrived. UKAEA has therefore examined field data to determine whether this factor could provide the basis for a method of determining how long particles had been on the beach (Hall and Toole 2007). The following data were collated for 17 particles: particle reference number, particle activity, depth of find, designated as H and R, activity concentrations in the sand and the mass of sand collected. The results are given in Fig. 3.5 (based on Fig. I in DPAG/2007/M41/007). Transfer of activity to the sand occurred with each particle and has been proportionately the lowest with the highest activity particle. The three H particles have particle activity: sand specific activity quotients that ranked 2nd, 3rd and 7th in the list of seventeen particles.

3.3.6 The results confirmed that there was a loss of activity from particles to surrounding sands. However, there was no conclusive demonstration that the levels of contamination in the sand showed a sufficiently strong correlation with residence time for this factor to provide a useful marker for assessing how long a particle has been present in the sand. The lack of a formal sample collection regime may account for some of the variation. There was no consistency between the amount of sand collected with each particle or the way in which it was collected. Even if the sampling regime could be refined to ensure that the same volume of sand surrounding the particle was collected in every case, there is still a possibility that minute fragments of a particle might contribute to the activity measured in the sand sample. Furthermore, it is possible that smaller particles might lose radioactivity at a faster rate than larger ones. If this proved to be the case, it would be difficult to correct for size differences, given the irregular shape of the particles. DPAG's main concern with this approach, however, was that, given the continual mobility of beach sediment, any activity lost could be rapidly dispersed away from the parent particle.

3.3.7 It is concluded that it is not possible to determine the residence time of particles using this method. However, the potential importance of diffusion into pore water has been quantified under controlled conditions in the laboratory. The fact that particles do lose activity to the surrounding sediment means that there will be a small dispersal of radioactivity with time, which will contribute to a reduction in the hazard associated with every particle.

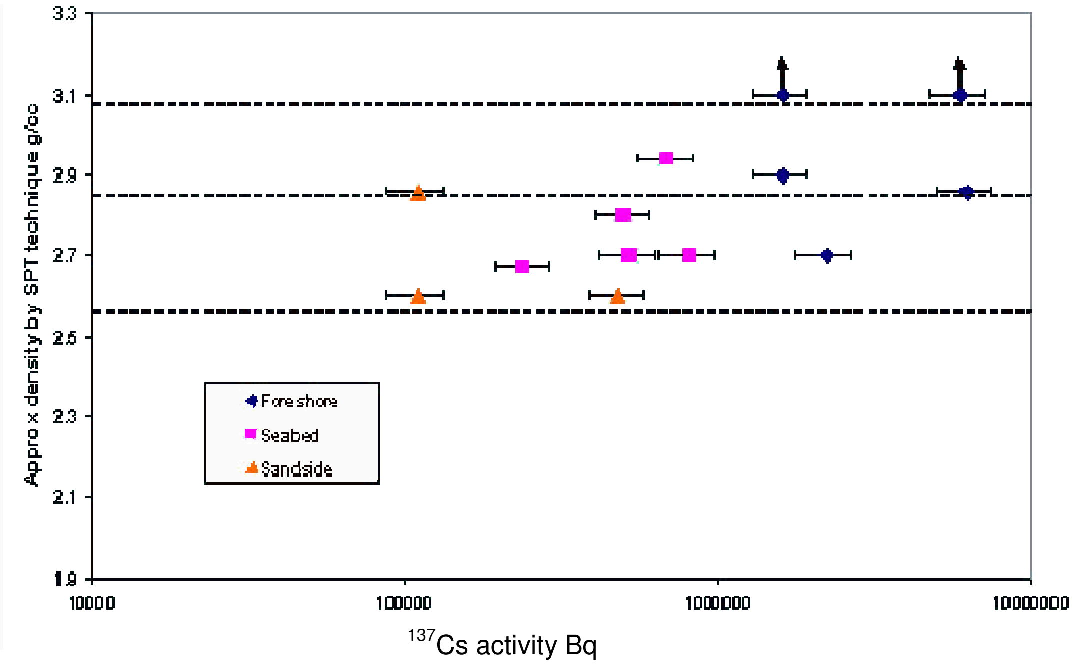

Fig. 3.1 Densities of MTR particles by location and ^{137}Cs activity

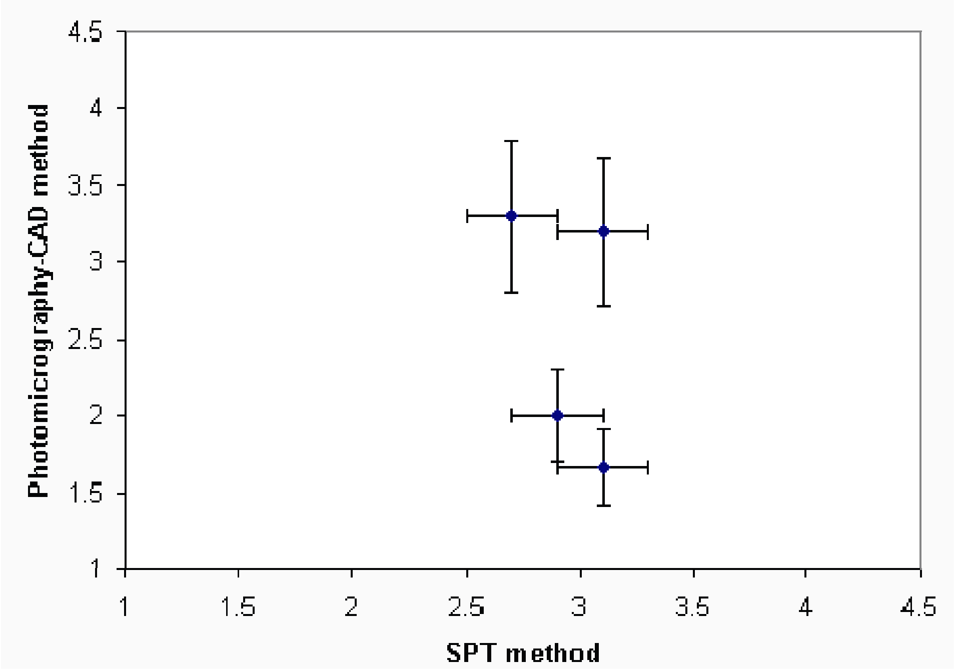

Fig. 3.2 Comparison of estimates of density

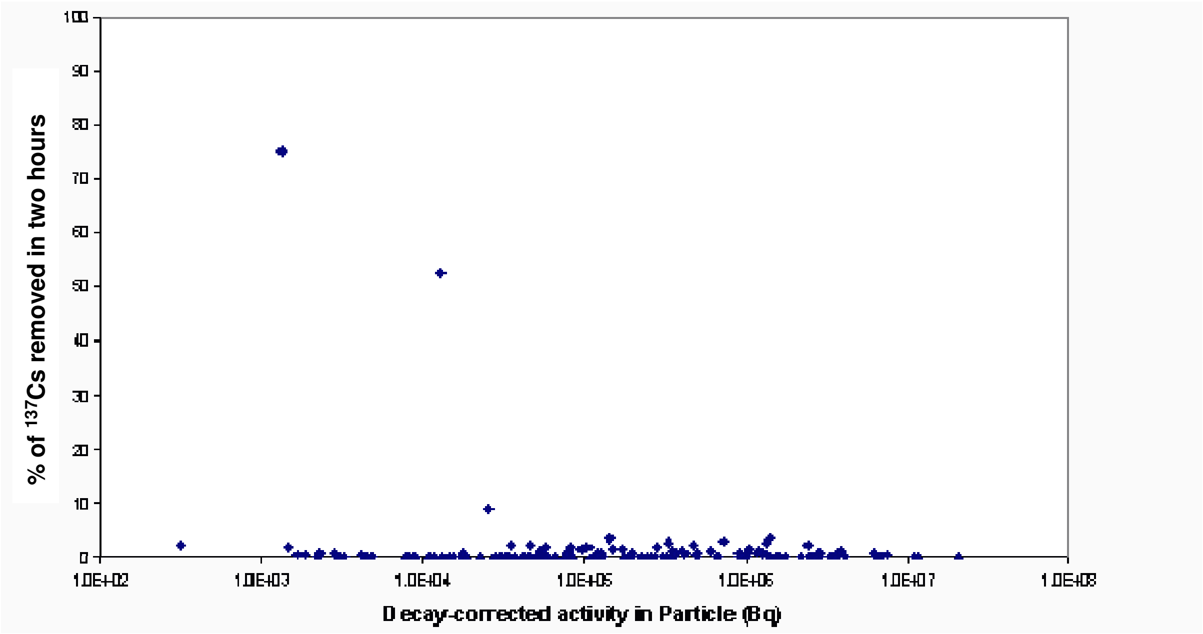

Fig. 3.3 Proportion of ^{137}Cs leached by pH2 HCl at 37°C

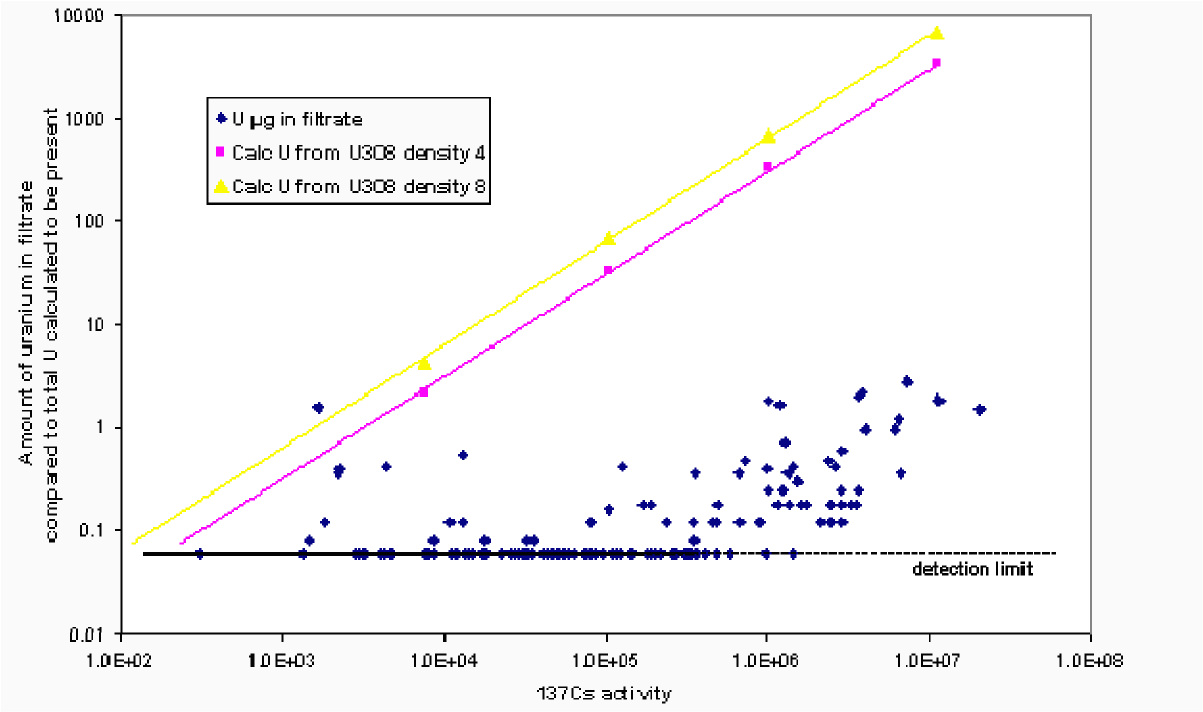

Fig. 3.4 Loss of uranium from particles (micrograms)

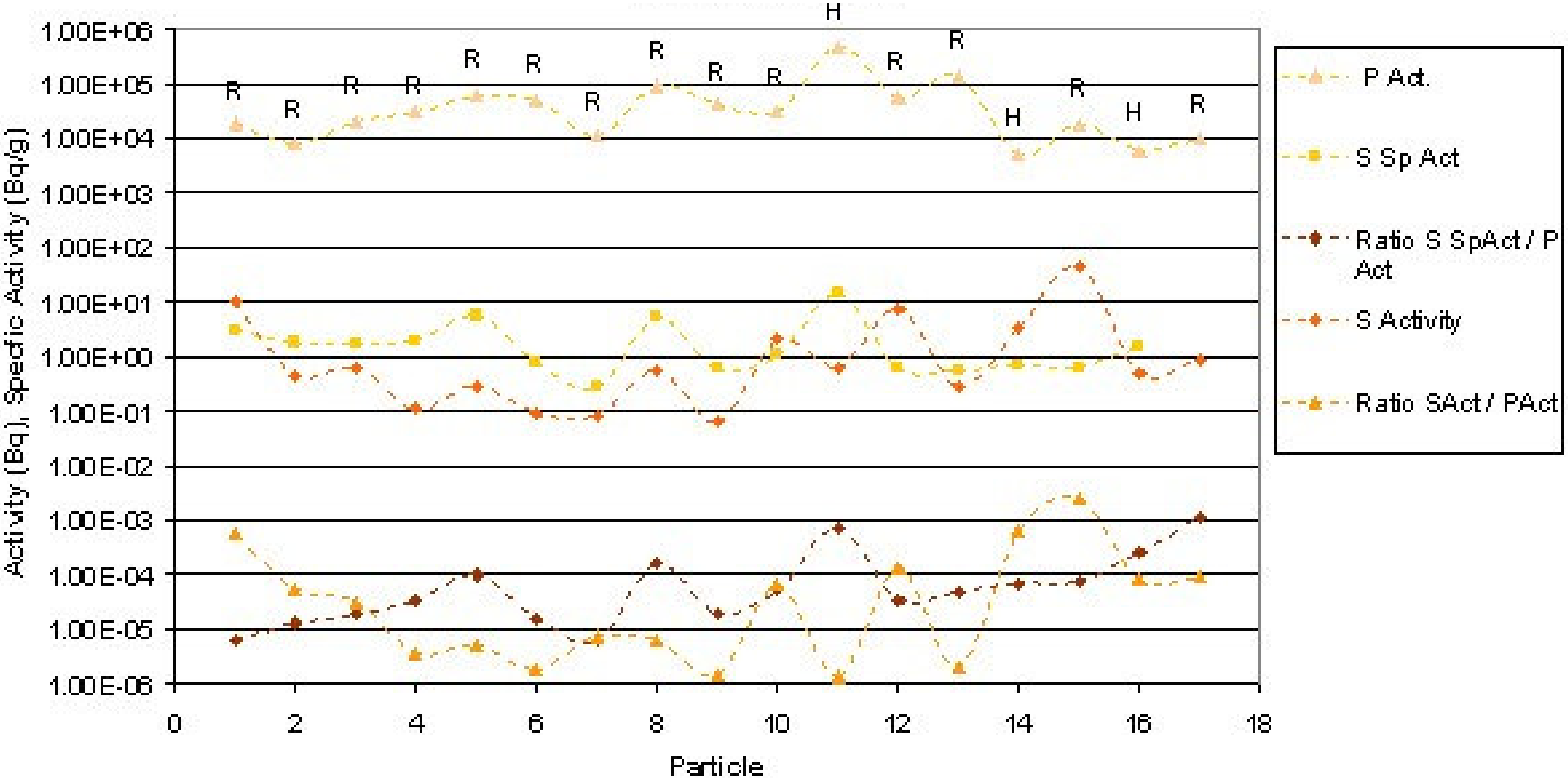

Fig. 3.5 **Comparison of particle (activity) and sand (activity and specific activity)**

4. Detection Systems

4.1 Introduction

4.1.1 Since the first positively identified fragment of irradiated nuclear fuel (a particle) was found on the Dounreay Foreshore in 1983, particles have been routinely detected in the offshore and coastal areas of Dounreay, in addition to the Site itself. Whilst strandline monitoring continued with hand-held Geiger counters, it was not until 1999 that widespread systematic monitoring of beach areas commenced. The introduction of the Groundhog systems provided a mechanism for public reassurance and prompt particle retrieval, whilst also providing a data set from which a better understanding of particle arrival characteristics could be achieved. In June 1997, the first known particle was discovered in the offshore environment by a diver, as part of engineering work in the vicinity of the Old Diffuser (OD) outlet. This brought forward plans to survey the sea bed, initially by divers and later by towed detection systems.

4.1.2 Since its inception, DPAG has worked to assess whether appropriate detection systems and methodologies are in place to: i) enable the prompt detection and recovery of particles; ii) provide public reassurance for public beaches; and iii) provide robust data with sufficient coverage to improve our understanding of the distribution and fate of particles in the offshore and coastal environment. This Chapter provides an update to the previous DPAG reports on the progress made by UKAEA, with its associated contractual organisations, to achieve these goals. The current detection systems deployed in the offshore and beach environments are also outlined.

4.2 Marine Systems

Historical Perspective

4.2.1 Having identified the presence of particles around the OD in 1997, further survey work of the sea bed was undertaken in August and September of 1997 by divers. These surveys were conducted to a distance of 600 m offshore and to a water depth of 20 m, yielding an additional 34 particles. A total of 35 particles are therefore recovered from an area of 21,200 m^2. As a result of these finds, and following advice from SEPA, the then Scottish Office imposed a FEPA Order[8,9].

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[8] The full title of the Order is the Food Protection (Emergency Prohibitions) (Dounreay Nuclear Establishment) Order 1997 an order made under the Food and Environment Protection Act 1985

[9] As a result of the sea bed finds in 1997, a FEPA Order was imposed restricting the taking of all seafoods in an area of radius 2 km, centred at the end of the outfall pipe (600 m offshore).

4.2.2 Over the summer of 1998 and spring 1999, diver surveys continued and the NaI(Tl) detectors used in 1997 were replaced with more sensitive plastic scintillation detectors. A further 140 particles were detected in a surveyed area of 137,000 m^2; of these 104 were recovered. Difficulties in surveying by divers in deeper water necessitated the deployment of a remote sensing system for particle detection. The Fathoms Instrument Towed System (FITS) was deployed in September 1998 and initially comprised a single plastic scintillation detector, later replaced by two scintillation detectors held 500 mm apart (FITS2). Between September 1998 and August 1999 a total of 23 separate surveys were undertaken that involved towing parallel to sea-bed contours, covering an area of 150,000 m^2. In our First Report (DPAG 2001), DPAG identified several shortcomings of the FITS data, primarily relating to its inability to discriminate the variation in the natural background from possible particle detection. Despite these limitations, UKAEA attempted to reconstruct offshore particle abundances by combining a model of the particle detection capability, accounting for anomalous high count rates by using running means to define trigger levels, and converting the number of count rate values which exceeded the threshold into a particle population distribution. Whilst some limited verification was undertaken by diver surveys, the model remained difficult to validate due to the nature and number of assumptions that underpinned it. Nevertheless, whilst diver surveys lacked the continuous cover of the FITS data, the combination of the two approaches coupled with some mechanistic interpretation by DPAG provided the first insight into the likely distribution of particles in the offshore environment. Most of the spatially isolated and very high count rate responses appeared to be limited to a line trending NE of the OD.

4.2.3 Further survey work of particles in the offshore environment was undertaken by divers for a variety of projects with different aims in understanding particle distribution and behaviour, including repopulation studies, detailed in our Second Report (DPAG 2003). In response to DPAG's recommendations to investigate the use of gamma spectrometry-based systems to explore the anomalous high background offshore environments identified by the FITS survey and to negate the risks associated with diving, UKAEA contracted Fathoms Ltd to deploy a marinised 76 mm x 76 mm NaI(Tl) detector for a fifteen day trial in September 2003 (Toole *et al*. 2006). The results, although spatially limited, demonstrated that the anomalous zone to the N of the area identified as a likely plume was characterised by a background dominated by high natural radioactivity. Having demonstrated the efficacy of deploying a sea bed NaI(Tl) based system, UKAEA decided to implement Remotely Operated Vehicle (ROV) technology to characterise the offshore environment. Following a tendering exercise, Fathoms were awarded the contract and deployed the TROL a twin tracked ROV for more controlled particle detection using a large volume NaI(Tl) detector. This started a programme of work in 2004 to search and remotely characterise particles (activity and depth) in the offshore environment, initially without the capability for particle retrieval.

The TROL System

4.2.4 Fig. 4.1 shows the TROL system deployed on the sea bed. It comprises a twin tracked ROV connected *via* umbilical to the surface where it is controlled from the ship *via* camera feedback. A marinised 102 mm x 102 mm x 406 mm

NaI(Tl) detector rated to 100 m depth is coupled to a SAM-935 signal processing system and is supported in front of the ROV. Initial results demonstrated significant drift in the ^{137}Cs peak location within the gamma ray spectrum. Auto-energy stabilisation was introduced by monitoring the location of the ^{40}K peak, which is assisted by the addition of KCl inside the marinised housing. The addition of the KCl ensures spectral stability, but at the expense of increased scattering of secondary gamma photons within the ^{137}Cs window that may marginally reduce ^{137}Cs detection sensitivity.

4.2.5 The TROL's operational measurement (integration) time is one second at a velocity of 0.35 ms^{-1}. The system is activated by a Full Alarm (count rate based on the whole spectrum), ^{137}Cs alarm and ^{60}Co alarm. Normally the alarm was set at 3σ of the background counts but this was increased for the Full trigger to reduce the number of false positives. When any of the pre-set thresholds is exceeded, the TROL system is manoeuvred to acquire a spectrum and a particle is only identified when the presence of ^{137}Cs, ^{60}Co or ^{94}Nb is recorded in the spectrum (Toole *et al*. 2006). The measurement time over the particle for spectrum acquisition is typically between one and 10 minutes, depending on the count rate observed by the operator.

Comparison of TROL Particle Detection Efficiency with Diver Surveys

4.2.6 In 2005, a trial was undertaken on the seabed in an area with a centre point 300 m NW of the Old Diffuser (OD), covering 2,500 m^2. The area was adjacent to known areas of high particle density but had not been surveyed previously. The TROL was deployed first and immediately followed by the divers. The divers marked each contact with a pin and did not retrieve the particles. The TROL was then redeployed to take static spectra at each location. Ten of these locations were cored to provide depth and activity estimates to refine a model for the remote determination of particle activity and depth. The divers were deployed with a plastic scintillator, of volume 206 cm^3, supported on the end of a crutch. The plastic scintillator was deployed *via* arc-like sweeping movements across the sea floor. An alarm is triggered when the count rate is greater than 3 σ of the background. The diver is alerted to the alarm *via* an audible signal, an LED display on the instrument and in the ship's control cabin. The dive-supervisor is also able to inform the diver directly of an alarm (Innes *et al*. 2006).

4.2.7 The positional accuracy of the TROL survey was no better than ± 4 m and consequently it was difficult to resolve particles in close proximity to each other. In addition, not counting particles located close to the perimeter rope of the survey area, which was avoided by the TROL, the TROL located 27 particles compared with 31 particles located by the diverse (Innes *et al*. 2006). By taking account of the presence of mobile particles, the inaccessible edge of the survey area and the inability spatially to resolve particles, the TROL was estimated to have a detection efficiency of around 90% relative to diver finds.

Fig. 4.1 The TROL System deployed in the Dounreay offshore environment

Remote Detection of Particle Activity and Depth

4.2.8 UKAEA has developed the capability of estimating the depth of a particle in the sediment and its activity from a measure of the proportion of forward Compton scattering relative to the area under the ^{137}Cs full energy peak. By using a combination of laboratory measurements and particles recovered from the comparison work, described in section 4.2.3, reasonably robust calibrations were derived for the depth of particle burial (Fig. 4.2) and particle activity (Fig. 4.3). The depth to which these relationships hold will be limited by the activity of the particle itself and Fig. 4.4 shows the accuracy of the technique by comparing the modelled particle activity estimated *in situ* with actual activity of particle measured in the laboratory. The comparison suggests that there may be a 10% overestimation in particle activity from the TROL calibration compared with the laboratory calibration. Later validation exercises indicate that a 30% overestimation is likely, as in Section 4.3.3.

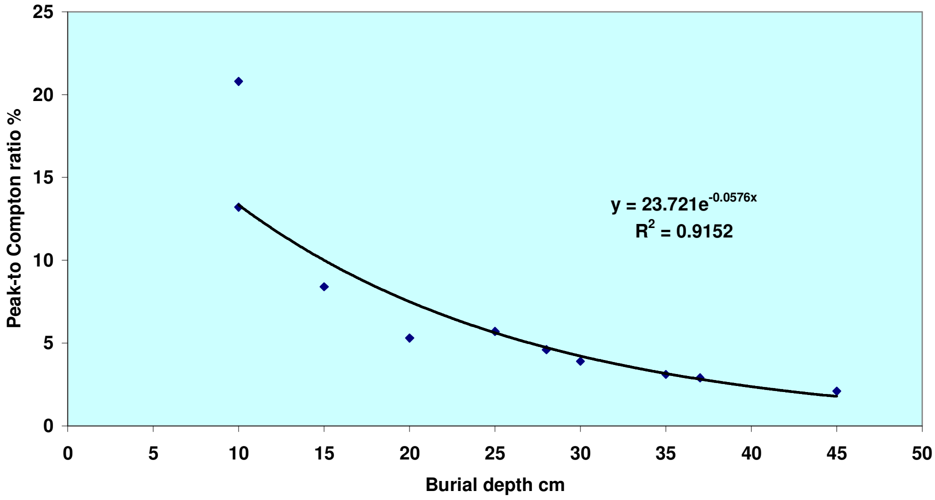

Fig. 4.2 Calibration curve for the *in situ* estimation of the depth of burial for a particle (Innes *et al.* 2006)

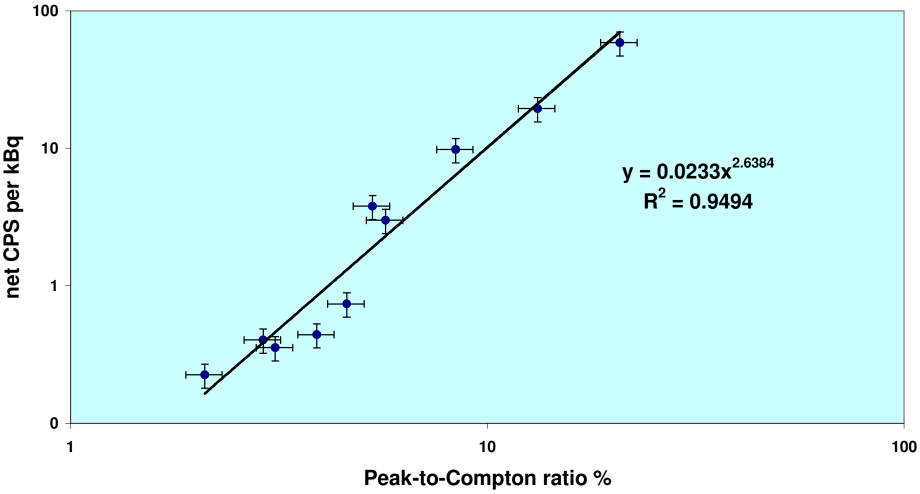

Fig. 4.3 Calibration curve for determining the appropriate *in situ* calibration coefficient for converting observed cps to the activity of the buried particle (Innes *et al*. 2006)

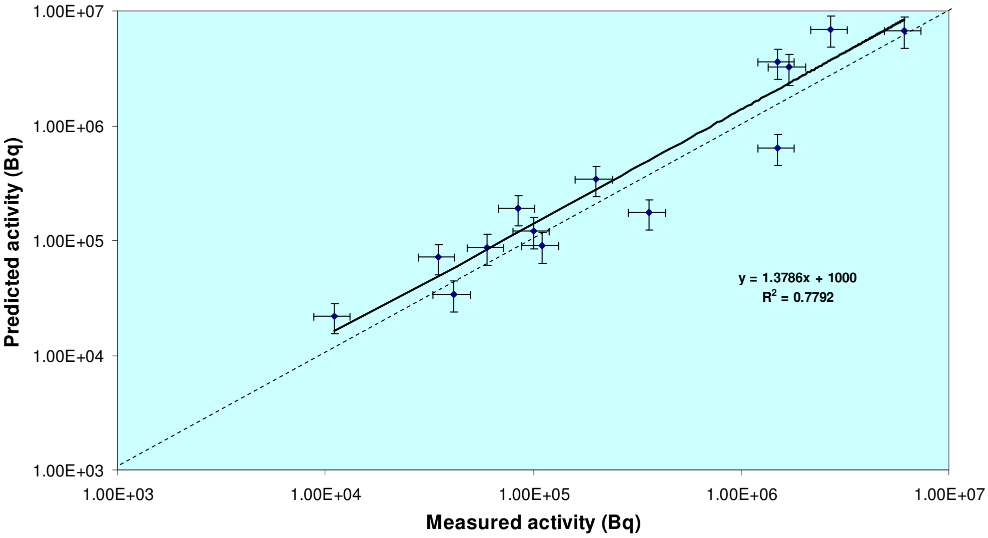

Fig. 4.4 Comparison between *in situ* TROL estimated activity and laboratory measured particle activity (Innes *et al.* 2006)

4.2.9 Currently, the technique works for ^{137}Cs particles which account for about 99% of particles retrieved so far. The technique could be adapted for ^{60}Co dominated particles. Nevertheless, this approach adds substantial value to the survey work offshore enabling contacts to be characterised without the need for collection and laboratory-based analysis. This approach, therefore, has the potential to facilitate the targeted removal of particles identified as *significant* (> 10^6 Bq ^{137}Cs).

Implementation of TROL

4.2.10 The TROL system was deployed on the sea bed adjacent to the Dounreay nuclear facility over the summer of 2007. The areas surveyed are summarised in Table 4.1 and were selected, in part, to refine our understanding of the footprint of the particle plume, possible pathways for particle migration and to validate, or otherwise, sites identified by the Wallingford Model as likely areas for particle caches. The surveyed areas consisted primarily of sand and/or gravel. A total of 69 particles was identified in a total surveyed area of 112,500 m^2. One of these particles was identified as ^{60}Co, whilst the remainder were all ^{137}Cs, with activities ranging from 10^3 to 10^7 Bq and estimated to range from the surface to around 500 mm depth.

4.2.11 Table 4.1 summarises the finds within all of the chosen survey areas. It is noticeable that all the particles measured W of the OD were either *minor* or *relevant* particles, with the highest activity predicted of 8.6x10^5 Bq ^{137}Cs. Whilst a particle has previously been located in the Brims Ness area, no particles were found during the TROL survey, although this may in part be explained by the small area surveyed. The highest mean activity (3.3x10^7 Bq ^{137}Cs) and particle frequency distribution (approximately one particle per 140 m^2) were identified in the area inshore of the OD and in a westerly direction.

Table 4.1 Summary of TROL Particle Contacts, Summer 2007

Area	Nominal Coverage Target (m^2)	Sub Area	Actual Area Surveyed (m^2)	Number of Contacts	Area per Particle (m^2)	Mean and Range Particle Activity Bq ^{137}Cs	Mean and Range Depth (mm)
1 Inshore of the Diffuser Outfall	15,000	E of Diffuser	6,900	11	627	1.2x10^{6} (2.9x10^{3}-5.9x10^{6})	140 (0-340)
		W of Diffuser	3,900	28	139	3.3 x10^{7} (9.2x10^{2}-6.4 x10^{8})	230 (0-490)
2. W of Diffuser towards Sandside Bay	75,000	Sandside Bay (Inshore)	12,600	6	2,100	1.7 x10^{5} (2.0x10^{4}-3.7 x10^{5})	140 (0-230)
		Sandside Bay (offshore)	27,500	8	3,438	3.6 x10^{5} (1) (1.5x10^{4}-8.6 x10^{5})	130 (0-370)
		Shore Parallel transects	32,300	14	2,307	1.3 x10^{5} (2) (1.3x10^{3}-3.4 x10^{5})	120 (0-450)
3. E of Diffuser distal to the main plume	15,000	Testing edge of the Plume	24,500	2	12,250	3.6 x10^{4} (5.5x10^{3}-6.7 x10^{4})	15 (0-30)
		Brims W	150	0	N/A	N/A	N/A
		Brims E	4,600	0	N/A	N/A	N/A
Totals	105,000		112450	69	Mean = 1630		

1. Means derived from seven of eight due to one particle identified as low activity close to the surface, but full energy peak too small to be useable in the model, and not recovered by diver.
2. Particle identified as a strike, but mobile and unable to be relocated for the acquisition of a longer *in situ* count.

4.2.12 One particle estimated as greater than 10^{6} Bq ^{137}Cs was recovered at 50 mm depth but when analysed in the laboratory it was found to contain 1.3x10^{3} Bq of ^{137}Cs. This overestimation, or false positive, is likely to be due to statistical noise in the forward scattering of the gamma spectrum. When particle activities are low and located close to the surface, the contribution of forward-scattered gamma photons is likely to be low. Under such circumstances, there is a higher probability that the forward-scattered portion of the spectrum will be noisy and elevated above the theoretical level for the given activity and geometry. When this is combined with a weak full-energy peak a false positive may result (*i.e.* an estimate that the particle is of higher activity and more deeply buried). Conversely, when a higher activity particle is present either close to the surface or at depth, there will be much stronger full-energy peak, or many more contributions to the forward-scattered region of the spectrum. Thus a false negative (*i.e.* an underestimation of particle activity – closer to the surface) is less likely to occur. Whilst occasional false positives from low activity particles cannot be ruled out, longer integration times when acquiring a gamma spectrum above a particle would reduce their likely occurrence.

4.3 Assessment of the ROV System by Comparison of ROV and Diver Finds

4.3.1 Fig. 4.5 shows the predictions of particle depths and activities for all of the ROV strikes made in 2004-7. Because the method is based on correlation of the relative proportion of forward Compton scattering with depth, predicting the depth of a particle that is very near the surface will involve extrapolation beyond the range of data used to derive the algorithm. This extrapolation and associated uncertainties can produce a prediction of negative depth. However, tabulations of the ROV strikes (*e.g.* on the UKAEA Website www.dounreay.com/particle-cleanup/particle-finds) normally place the predicted depths of shallow particles into a single category of 'less than 100 mm'. Almost 20% of strikes had predicted depths <100 mm, but only *c.* 4% were predicted to have negative depths.

4.3.2 Similar considerations regarding extrapolation beyond the range of calibration data apply to predicted depths greater than about 500 mm, and to predicted activities greater than 10^7 Bq ^{137}Cs. Fig. 4.5 shows the ROV data, but with all predicted depths less than 100 mm plotted as an arbitrary value of 90 mm, and all depths greater than 500 mm plotted as 510 mm. Predicted activities greater than 10^7 Bq are plotted as 1.1×10^7 Bq ^{137}Cs.

4.3.3 ROV predictions of particle activity could be compared directly with the true activities for four particles that were recovered by divers after first being located by the ROV. In all four cases, the ROV algorithm predicts an activity that is higher than the value measured in the laboratory, with the average difference being around 30%. Although this appears at first sight to be evidence of systematic over-estimation by the ROV, the number of cases is so small that the result could have arisen by chance. For example the probability is *c.* 6% that a measurement device that was subject to an unbiased random error would overestimate true values in four successive cases. Although the average size of the discrepancies may also seem quite large, at 30%, none of them looks anomalous when compared with the overall scatter in the predicted activities for all particles with similar predicted depths. More data are needed before the accuracy and precision of ROV predictions of particle activities can be properly assessed.

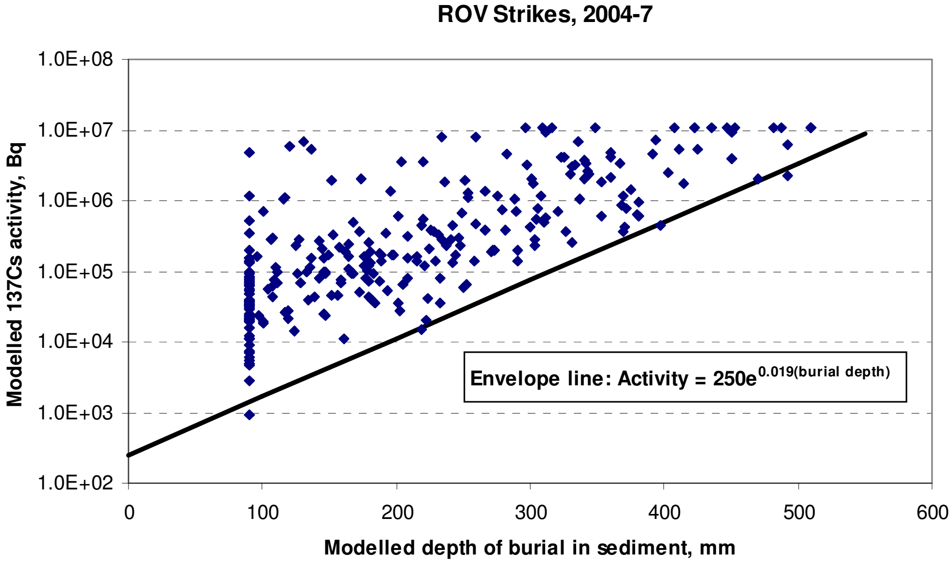

Fig. 4.5 **Depths and activities of ROV strikes as predicted (modelled) from UKAEA algorithm with all predicted depths less than 100 mm plotted as "90 mm" and predicted activities greater than 10^7 Bq ^{137}Cs plotted as "1.1x10^7 Bq"**[10]

4.3.4 A different approach to assessing the results of the ROV surveys is to compare them with equivalent findings from diver surveys. Such a comparison can only be made at the level of statistical distributions of results, and should be interpreted cautiously because the areas surveyed by the two methods are different, as discussed in section 5.1. Fig. 4.6 compares the percentage distributions of ROV and diver finds with depth of burial in sediment. ROV data are predicted depths, whereas for diver finds the depth is the value recorded by the diver at the time of excavation of each particle; this in itself has an associated inaccuracy.

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[10] The envelope line defines the lower limit of the data.

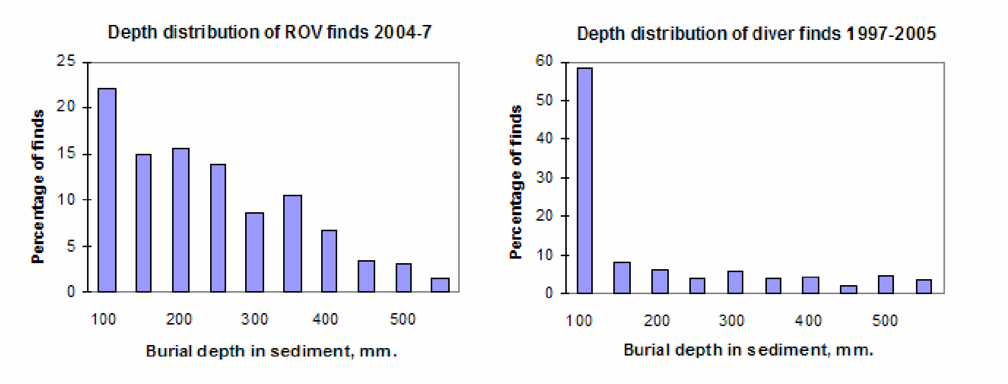

Fig. 4.6 Comparison of depth distributions between (a) predictions for ROV strikes (left panel) and (b) recorded depths for diver finds (right panel)

4.3.5 Both sets of data show a decline in particle frequency with depth, but there is a striking difference in the frequency for those particles buried at depths of less than 100 mm. Over 50% of diver finds occur in this category, whereas only about 20% of ROV strikes have such shallow predicted depths. This may, at least in part, be explained by the problem of low activity particles close to the surface being misclassified as high activity particles at depth, as described in section 4.2.5. Fig. 4.7 provides a comparison of finds assigned to depths greater than 100 mm and demonstrates that these data are more consistent. The ROV predictions (Fig. 4.7(a)) show frequencies that decline fairly steadily at depths greater than 200 – 250 mm. The diver finds are more irregularly distributed, but also show a decline in frequency with depth. However, the diver data show a higher proportion of particles below 450 mm. It is possible that this reflects a systematic overestimation of depths during excavation of deeply buried particles from loose sand on the sea floor, because the reported depths of the deepest diver finds were greater than was theoretically possible, given the sensitivity of the equipment employed. With these limitations, it appears that the ROV and diver surveys give broadly comparable results for the statistical frequencies of depths of detected particles greater than 100 mm. However, the two methods differ markedly in the proportions of particles attributed to depths less than 100 mm.

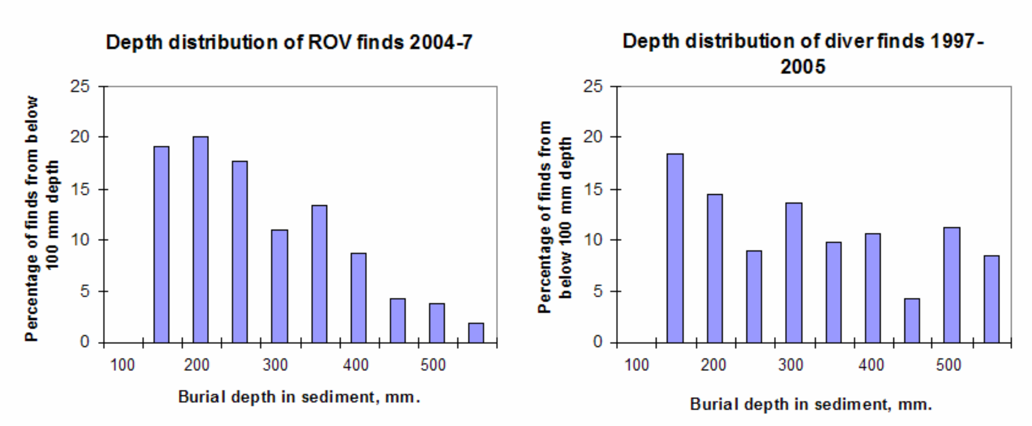

Fig. 4.7 A more detailed comparison between (a) depths predicted for ROV strikes (left panel) and (b) recorded depths for diver finds (right panel)

4.3.6 The frequency distribution of predicted activities among ROV particles is compared with diver finds in Fig. 4.8. The category size is roughly one quarter of the range of scatter in ROV predictions for any given depth. The two distributions are visually distinct. The range of activities predicted by the ROV is similar to the diver finds (apart from an absence of very low activity particles $<10^3$ Bq ^{137}Cs), but there is a shift of the most abundant classes towards higher activities. Again, this may reflect the problem of low activity particles close to the surface being misclassified as high activity particles at depth (section 4.2.12). This difference probably reflects the larger overall size of the diver data set (N=834 for diver finds, N=268 for ROV predictions) and its greater proportion of shallow finds. Low activities can only be detected if particles are close to the surface. Taken together, these results suggest that divers may be somewhat more efficient than the ROV in locating lower activity particles at very shallow depths. In addition to the explanation presented in section 4.2.12, it may also be possible to explain the differences in the abundance of low activity particles found by the contrasting methods of search employed by the divers and the ROV. The ROV passes systematically back and forth across a small, defined area, whereas the early searches by divers were made non-systematically and extensively and so could have been biased towards detection of shallow particles.

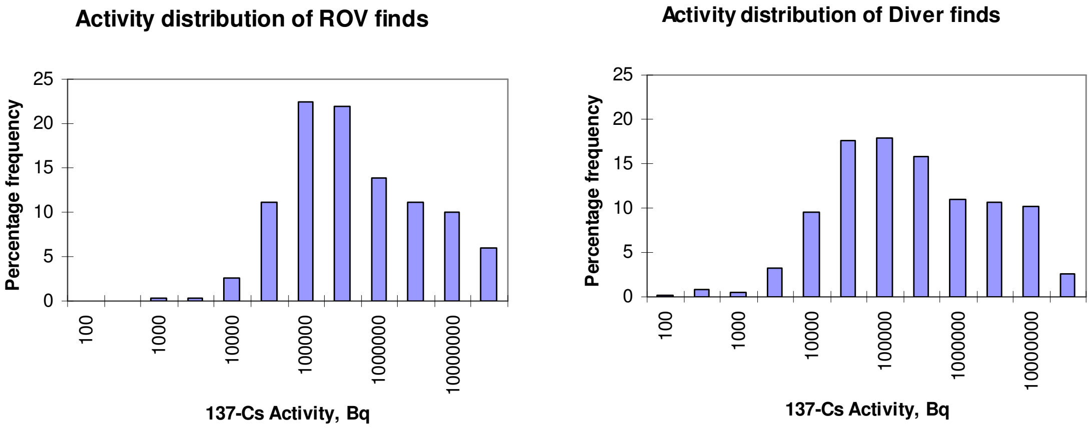

Fig. 4.8 Comparison between frequency distributions of (a) predicted ^{137}Cs activities of ROV strikes (left panel) and (b) measured activities of diver finds (right panel)

4.3.7 A final basis for statistical comparison between ROV and diver finds is to consider depths and activities in combination. Fig. 4.5 shows ROV predictions of activity plotted against depth, and shows the “envelope line”. This line is also plotted on Fig. 4.9 which shows activity *versus* depth for the diver data. This figure also shows the theoretical detection limit of the detector system used by divers, as a yellow line. This comparison suggests that the theoretical sensitivity of the divers’ system is greater for detecting deeply buried particles. At the surface the two systems have the same detection limit (*c.* 2.5 x 10^2 Bq ^{137}Cs), but at 500 mm the divers’ system has a theoretical advantage of 500 kBq ^{137}Cs in particle activity. This difference is borne out by the distribution of actual data for diver finds, which conforms moderately well to the theoretical limit. Only 2% were reported by divers to come from greater depths than the theoretical detection limit. The majority of these probably reflect overestimation of depth, although a few might have been found as a result of a diver responding to a slight increase in count rate by resting the detector over the spot above the particle for longer than is assumed in the derivation of a theoretical detection limit. By contrast with this, the “envelope line” for the ROV data passes well inside the scatter of diver finds, suggesting the somewhat lower sensitivity of the ROV system for detecting buried particles.

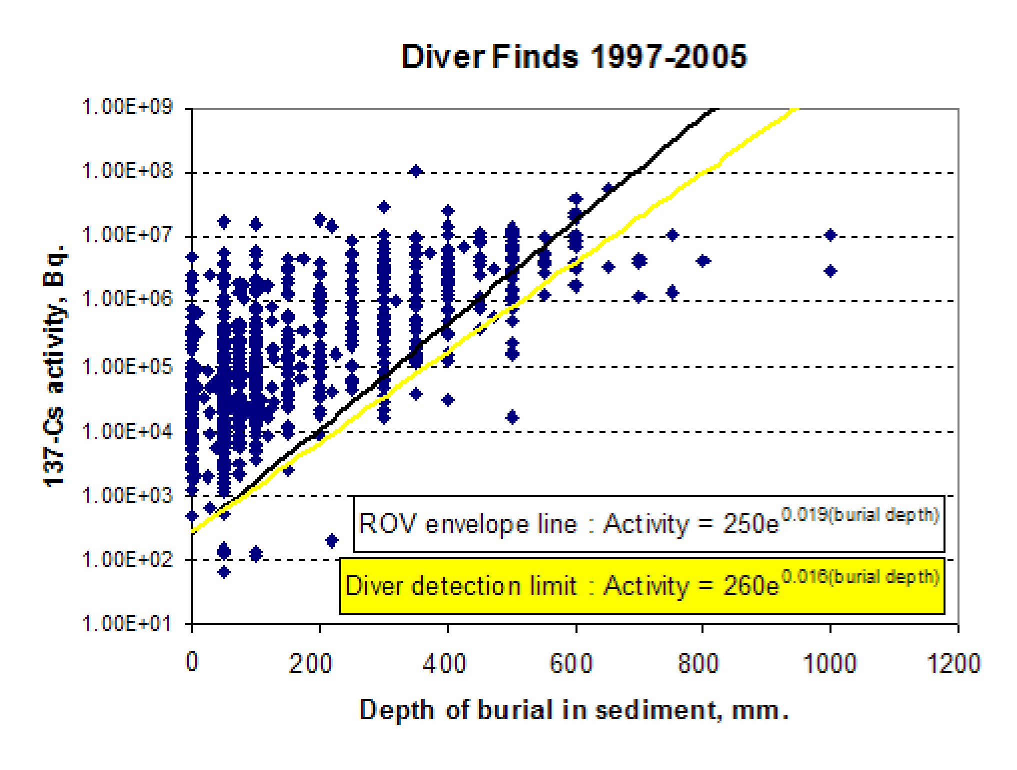

Fig. 4.9 **Relationship between recorded depths and measured activities of diver finds. The yellow line shows the theoretical detection limit of - the monitoring equipment used (from M.Scirea (2000). Dounreay offshore particles: burial depth in sea bed distribution analysis. UKAEA EMPD(00)16, 23pp). The black line shows the bounding envelope of the predicted depths and activities for ROV strikes (from Fig. 4.5(b) in this report)**

Summary and Conclusions

4.3.8 The TROL system represents a significant advancement in offshore particle detection, providing the ability to distinguish particles from elevated natural background. The ability to provide remote detection and estimation of ^{137}Cs particle activity and depth provides substantial added value to offshore surveys. Its performance has been demonstrated to be similar to that of the divers, although there is a suggestion that the divers are more effective at finding higher activity, deeper particles. The ROV appears to have the potential of misclassifying low-activity particles close to the surface as high-activity deep particles. However, if all particles detected are recovered, as is proposed with the new automated approach, DPAG does not see misclassification as an important issue.

Developments in Offshore Remote Particle Retrieval Systems

4.3.9 UKAEA has undertaken trials of two offshore particle retrieval systems operated by Land and Marine and Fathoms. The trials were hampered by weather conditions over the winter months but retrieval capability was demonstrated to a limited extent. DPAG supports these technically challenging and novel developments. The success of their implementation will require careful review and should take into consideration the overall disturbance of the sea bed and particles in addition to their effective efficiency in particle retrieval. Within this context, once demonstrated to be successful, DPAG foresees that this would provide a valuable approach towards alleviating the problems associated with the offshore particles.

4.4 Beach Monitoring Systems

Introduction

4.4.1 An empirical and theoretical evaluation of Groundhog Mark 1 and Evolution was presented by DPAG in our Third Report (DPAG 2006). This included beach trials to validate the detection capability of the Groundhog systems (COMARE, 2006; DPAG 2006). A revised digital-based monitoring system, Groundhog Evolution 2, was introduced in January 2007. This section presents an evaluation of the operational performance of Groundhog Evolution 2, following a COMARE-led and DPAG-supported trial in June 2007.

4.4.2 The History of Beach Monitoring Around Dounreay

- **Dounreay Foreshore**
  Routine bi-weekly strandline monitoring has been carried out on the Dounreay Foreshore since 1983. Beta/gamma monitoring was carried out by means of hand-held Geiger-Muller tubes until June 2002. Subsequently, the surveys have been carried out using a hand-held single NaI detector system based on the Groundhog Mark 1 system, as well as beta surveys using a large-area beta detector. In October 2004, Groundhog Evolution was introduced. Since then, the Dounreay Foreshore has generally been monitored fortnightly, the exception being during the four months of the tern nesting season (1st May to 31st August). By March 2008, 255 particles have been detected and retrieved from the Dounreay Foreshore and the highest activity found on the Dounreay Foreshore is 2.0×10^{8} Bq ^{137}Cs (November 1991).

- **Sandside Beach**
  Following the first, well documented particle find on Sandside in 1984, no further particles were discovered on Sandside until 1997, when two particles were located. These finds resulted in an increase in the frequency of Sandside strandline monitoring from once every two weeks to once every week (alternately beta probe and beta/gamma probe) in line with advice given by COMARE in 1995. The Groundhog Mark 1 gamma detector system was first introduced for routine monitoring in July 1999 and replaced by Groundhog Evolution in November 2002, and Groundhog Evolution 2 in January 2007. Particles have continued to be found, retrieved and recorded. By March 2008, a total of 109 particles had been located, of which 50 have been located since February 2006. The highest activity found on a public beach was 5×10^{5} Bq ^{137}Cs at Sandside (February 2007). More detail of particle finds is presented in Section 6.

- **Other Beaches**
  In 2005, during a survey at Dunnet Beach, a small number of radioactive items were found. These included several stones with elevated concentrations of naturally occurring radioactivity, a particle of around 8×10^3 Bq ^{137}Cs and a piece of plastic containing around 2×10^4 Bq ^{137}Cs. In April 2007, Murkle was surveyed and a 1.3×10^4 Bq ^{137}Cs particle was detected and recovered. Other beaches (Melvich, Brims Ness, Crosskirk, Scrabster, Thurso and Peedie) have been surveyed, but no further particles have been detected.

Schedule of Beach Monitoring

4.4.3 A schedule specifying the beaches to be monitored and the frequency of surveying was issued by SEPA in February 1999. This was as part of SEPA's response to UKAEA's application to dispose of radioactive wastes from Dounreay. Following a review in 2000, a revised Technical Implementation Document (TID) was implemented in 2001. The main difference between the two TIDs were the detection criteria set. This requirement is now part of the Authorisation, the current requirement limits the speed of monitoring to ensure the system is capable of detecting *relevant* particles to a depth of at least 100 mm.

Groundhog Systems

4.4.4 In March 1999, UKAEA tested a vehicular (Unimog), mounted gamma ray detection system (Groundhog Mark 1) on the beaches at Thurso and Scrabster which utilised four independently operated 76 mm x 76 mm thallium-doped (sodium iodide scintillation detectors (NaI(Tl)). In July 1999, following discussion with SEPA, this system was brought into routine operation to fulfil the requirements of the TID. During the 35 months since its inception, this system located 17 particles on Sandside Beach.

4.4.5 SEPA's review in 2000 concluded that the 10^5 Bq ^{137}Cs detection criterion of the TID was not strictly being met under all circumstances. SEPA and UKAEA estimated independently that a detection level of 1.4×10^5 Bq ^{137}Cs was more typical for particles lying between the detectors at 100 mm depth. Following detailed theoretical considerations undertaken independently by DPAG and NRPB (now HPA-RPD), published in our Second Report (DPAG 2003), DPAG and NRPB expressed concerns that the Groundhog Mark 1 system was unable to meet the detection requirements of the TID. This was presented at an open meeting with DPAG, NRPB, COMARE, UKAEA and RWE Nukem in 2002. DPAG and COMARE recommended that further improvements should be made to the current monitoring strategy and equipment to ensure the TID was being met. UKAEA responded by reducing the monitoring velocity to *c.* 0.8 ms^{-1} and then replacing Groundhog Mark 1 by Groundhog Evolution in November 2002.

Fig. 4.10 2007 beach monitoring trial: Groundhog Evolution 2

4.4.6 The ‘Groundhog Evolution’ system incorporated five larger volume (76 mm x 400 mm) detectors mounted on the front of a Hillcat vehicle (Fig. 4.10) to provide a contiguous lateral cover of 2 m, representing a 6.7-fold increase in detector volume over the old Groundhog system (Fig. 4.11). The first system was deployed in November 2002 and after a brief period of operating up to 1.6 ms^{-1}, and in response to DPAG concerns and the requirements of SEPA, Groundhog Evolution’s monitoring velocity was reduced to 1 ms^{-1}. This effectively improved the system’s detection capability. A second replicate Evolution system was introduced in 2004.

4.4.7 In 2007, a new system (Groundhog Evolution 2) (Fig. 4.10) was introduced. The detection system is very similar to the original Groundhog Evolution; the counts from the detectors are recorded in a below ^{137}Cs window, ^{137}Cs window and an above ^{137}Cs window. The detectors are mounted on a Hillcat vehicle in an array maintained at around 200 mm above the sediment surface, although this geometry can vary to avoid irregularities on the beach. The electronics, however, have been upgraded, replacing analogue with digital signal processing, enabling the detection capabilities to be optimised *via* overlapping sub-second sampling of one-second integration times.

Beach Trials of Groundhog Evolution

4.4.8 COMARE and DPAG carried out an experimental validation of this system in April 2006, the results of which are detailed in both COMARE and DPAG publications (COMARE 2006; DPAG 2006). These tests, using sources containing 10^6, 10^5 and 10^4 Bq of ^{137}Cs, were carried out on Sandside Beach, where particles have been found.

Beach Trials of Groundhog Evolution 2

4.4.9 In December 2006, UKAEA notified COMARE and DPAG that an improved detection system, Groundhog Evolution 2, was ready to be deployed. Given the expected improvement in detection capability, SEPA made available the necessary funding to purchase a further set of Perspex-encapsulated point sources of ^{137}Cs comprising activities of 10^3 and 10^2 Bq.

4.4.10 Tests were scheduled to be carried out on the beach at Sandside Bay, but access could not be arranged. The tests were carried out on the beach at Dunnet Bay, access permission having been granted by the landowners: agreement was obtained also from the Scottish Executive (now the Scottish Government), SEPA and UKAEA. By examining maps of total gamma radiation from previous Groundhog surveys (Fig. 4.12), an area was identified that would provide a similar background to that observed during the majority of the trials on Sandside Beach.

4.4.11 The trials were carried out over the period 22-23 June 2007 by a small team representing both COMARE and DPAG, together with an observer from SEPA. The beach trials were designed to quantify the detection capabilities of the Groundhog Evolution 2 system.

4.4.12 In order to conduct the trials, UKAEA made available two Hillcat vehicles. Initially, one was configured as the original Groundhog Evolution system tested in 2006 and the other as Groundhog Evolution 2. The former was used to confirm that the performance at Dunnet Bay matched that at Sandside Bay in 2006; once this had been established, it was reconfigured as a second Groundhog Evolution 2. The vehicles were operated by experienced staff of RWE NUKEM, the UKAEA sub-contractor undertaking the routine beach monitoring programme. This ensured that the trials were carried out under exactly the same conditions as routine beach monitoring. Prior to setting up the experimental layouts on each day, the area to be used was surveyed by Groundhog Evolution 2 using standard operating procedures in order to ensure that there were no radioactive particles within the test area. This background survey extended at least 1.5 detector array widths to either side of the source positions and to at least the vehicle turning areas beyond both ends of every layout. Over the two days, some 5,000 m^2 of beach were surveyed and no radioactive particles were detected.

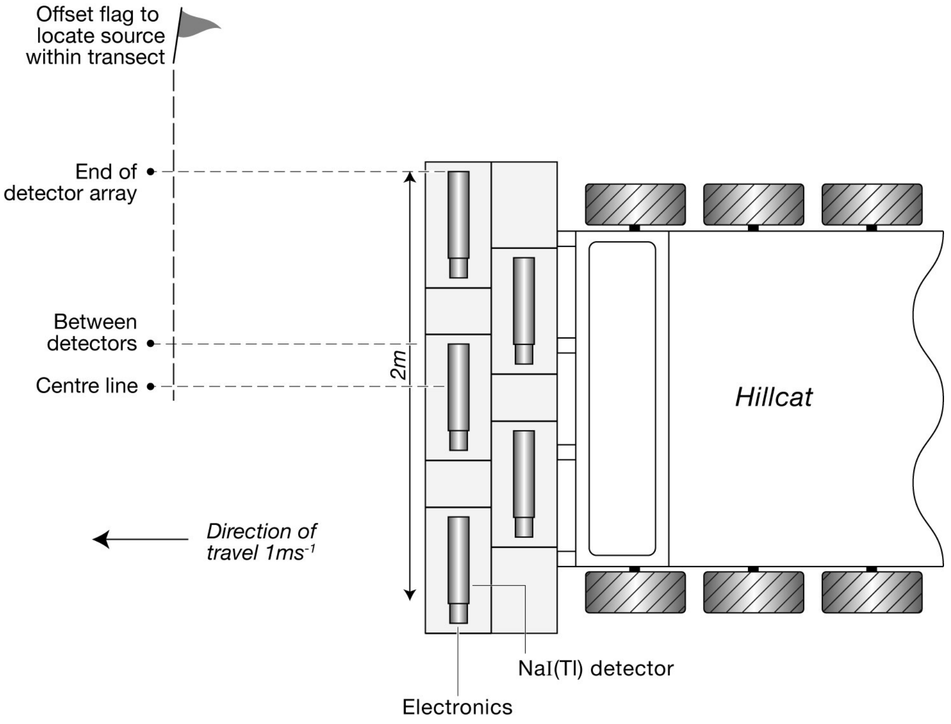

Fig. 4.11 Sketch plan of the detector array mounted on the front of a Hillcat for both Groundhog Evolution Systems (1 & 2) in relation to the deployment of sources for the beach trials

Test Areas

4.4.13 Test runs were constructed using 250 m lengths of beach, and two areas of the beach were used (Fig. 4.12). A linear array of sources was buried 15 m apart along the length of the transect, to the required depth. This distance was chosen in order to accommodate the requirement to reset the detector systems after each detection event. Over the course of the trials, sources were buried at depths of 0, 50, 100, 200, 300 mm below the surface and given the potential improvement in detection capability a new depth of 400 mm was introduced. Two new source strengths of 10^2 Bq, 10^3 Bq ^{137}Cs were also introduced to complement the existing 10^4 Bq, 10^5 Bq and 10^6 Bq of ^{137}Cs and 10^5 Bq of ^{60}Co sources used for the original trial.

4.4.14 The Perspex sources were held in a steel holder, retained in place by a clip-on PTFE cover. The position for each source was located by reference to a surveyor's tape laid along the length of each linear array of sources. The use of the steel source-holder also permitted location by means of a standard metal detector. The theoretical performance of the detector array may change dependent upon the location of any particle across the field of view. Fig. 4.11 illustrates the deployment of the sources with respect to the detector configuration. Three source detector geometries were identified to test: i) the optimal detector performance where sources pass directly under the centre of any given detector, ii) the offset configuration where sources pass between two detectors on the contiguous detector array, and iii) the worst case scenario, where sources pass under the edge of the detector array.

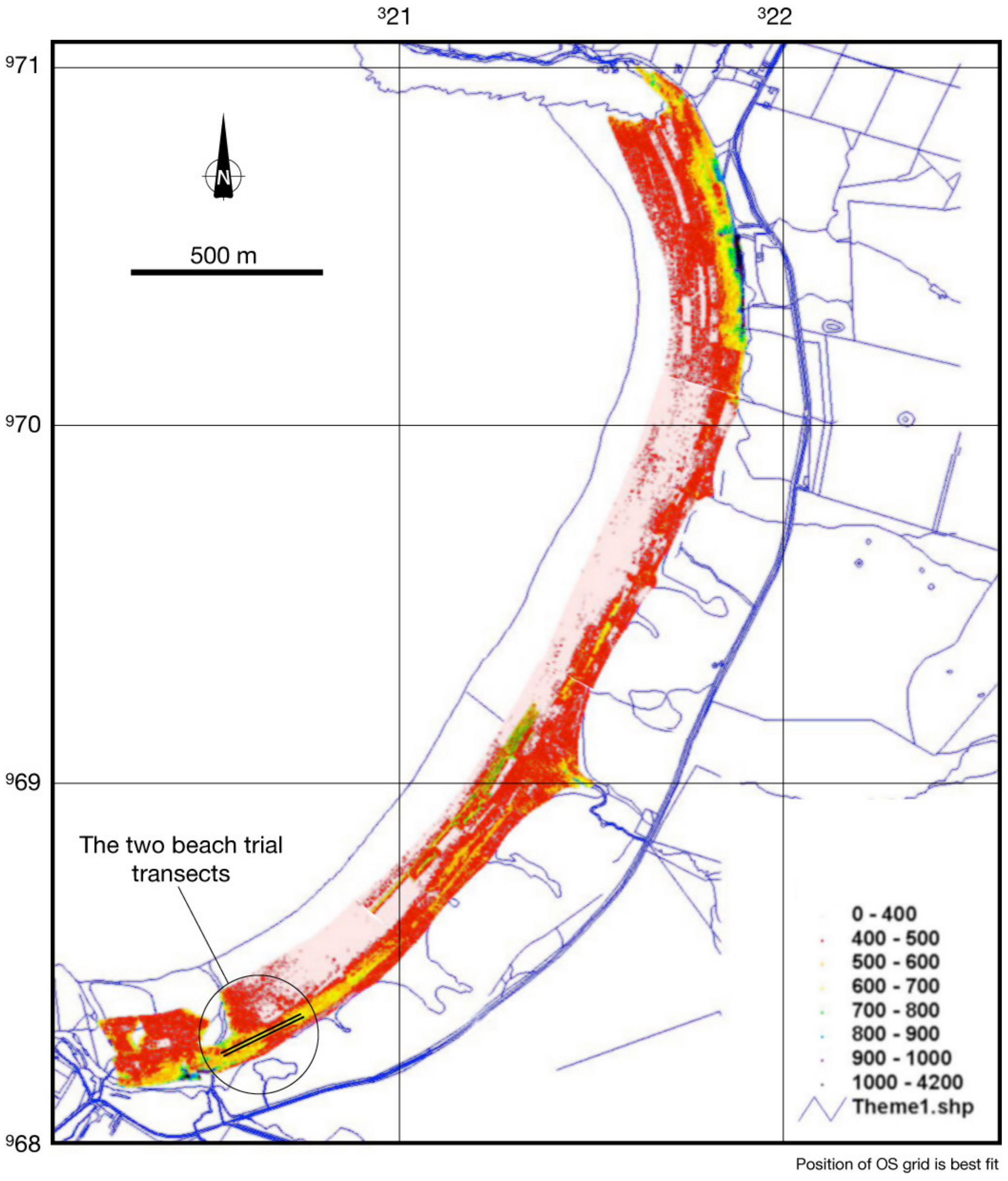

Fig. 4.12 **Map showing the location of the monitoring areas during the 2007 Dunnet Beach monitoring trials superimposed on top of a map of the total gamma ray background measured by Groundhog Evolution**

Numbers of Trials

4.4.15 From Appendix H8 of our Third Report (DPAG 2006) and assuming that the detection probability was better than 0.8, it was estimated that 25 measurements were required for each source/depth/lateral offset combination in order to have a reasonable degree of confidence on the probability estimate. This was obtained in all cases for sources with activity of 10^4 Bq ^{137}Cs and above. For the lower activities of 10^2 and 10^3 Bq ^{137}Cs, 250 measurements were carried out, although at the low levels of probability of detection, the uncertainties remain quite high. The approximate 95% confidence intervals (CI) on the probabilities of detection are quoted in Tables 4.2, 4.3 and 4.4.

4.4.16 The vehicles were operated at the standard monitoring velocity of 1 ms^{-1}. On each run, there was a lead-in blank area to ensure that the vehicle was at the correct operating speed on reaching the first target.

Results

4.4.17 Table 4.2 presents the mean results across the detector array from a low background region and Table 4.3 presents the results from an elevated background region from Groundhog Evolution, operating on Sandside Beach as reported in 2006 by COMARE and DPAG (DPAG 2006; COMARE 2006). These results demonstrated that a 10^6 Bq ^{137}Cs particle could be detected reliably by the system to depths of at least 300 mm. Groundhog Evolution had a probability of around 0.5 of detecting 10^5 Bq ^{60}Co source down to at least 200 mm depth, despite the system not being specifically configured to detect this radionuclide. The introduction of Groundhog Evolution made a substantial improvement over Groundhog Mark 1 on particle detection capability with 10^5 Bq ^{137}Cs particles being detected with almost 90% confidence to 200 mm depth.

Table 4.2 Groundhog Evolution results from the 2006 Sandside Beach trials for the Low Background Area. The probability is estimated as the proportion of successful detections out of 25 observations for ^{137}Cs and five observations for ^{60}Co

***Groundhog Evolution* detection probability** Mean Velocity = 0.98 ± 0.08 ms^{-1}								
	^{137}Cs						**^{60}Co**	
Depth	**10^4 Bq**	**95%CI**	**10^5 Bq**	**95%CI**	**10^6 Bq**	**95%CI**	**10^5 Bq**	**95%CI**
50 mm	0.76	0.55 0.90	1		0.96	0.79 0.99	0.5	0.18 0.81
100 mm	0.165	0.09 0.28	1		0.973	0.89 0.99	0.775	0.40 0.97
200 mm	0.013	0.00 0.07	0.88	0.78 0.94	1		0.6	0.32 0.84
300 mm					1			

Table 4.3 Groundhog Evolution results from the 2006 Sandside Beach trials for the Elevated Background Area. The probability is estimated as the proportion of successful detections out of 24 observations in most cases

Groundhog Evolution **detection probability.** Mean Velocity = 1.02 ± 0.11 ms^{-1}						
			^{137}Cs			
Depth	**10^4 Bq**	**95%CI**	**10^5 Bq**	**95%CI**	**10^6 Bq**	**95%CI**
100 mm	0.083	0.03 0.17	1		0.973	0.90 0.99
200 mm	0.028	0.00 0.10	0.903	0.81 0.96	1	

4.4.18 In the 2007 trials, UKAEA reproduced Groundhog Evolution and by repeating the survey with a series of 10^5 and 10^6 Bq ^{137}Cs sources, demonstrated that the performance was consistent with the 2006 trial, thereby providing some comparability with the 2006 Sandside Beach trials. Table 4.4 shows the data obtained during the 2007 trial for the Evolution 2 system. The data demonstrate the improved capacity of Groundhog Evolution 2 in detecting ^{137}Cs, with 10^6 Bq particles being reliably detected to at least 400 mm depth, 10^5 Bq particles to around 300 mm depth, 10^4 Bq particles to between 50 and 100 mm depth. Importantly, the results also show that should a large abundance of 10^3 Bq and 10^2 Bq particles exist, it is likely that a small proportion (between 9 and 4 % respectively) would have been detected.

4.4.19 In addition, tests were carried out with 10^5 Bq ^{60}Co sources at a depth of 300 mm. Using only the ^{60}Co window alarm, the detection probability was 66%. Using all alarm conditions, this probability increased to 96%.

Table 4.4 Groundhog Evolution 2 detection probabilities from 2007 Dunnet Beach trials

***Groundhog Evolution* 2 detection probability** Mean Velocity = 0.95 ± 0.05 ms^{-1}										
					^{137}Cs					
Depth	**10^2 Bq**	**95%CI**	**10^3 Bq**	**95%CI**	**10^4 Bq**	**95%CI**	**10^5 Bq**	**95%CI**	**10^6 Bq**	**95%CI**
Surface	0.044	0.023 0.074	0.087	0.057 0.12						
50 mm					0.84	0.74 0.91				
100 mm					0.74	0.60 0.85				
200 mm					0.20	0.12 0.31	0.88	0.76 0.95		
300 mm							0.81	0.71 0.89	0.94	0.83 0.99
400 mm							0.20	0.12 0.31	0.96	0.86 1.00

Conclusions

4.4.20 Groundhog Evolution is capable of meeting the original requirements of the TID, detecting a 10^5 Bq ^{137}Cs particle at 100 mm depth and approached our suggested target of 10^5 Bq ^{137}Cs at 200 mm at a monitoring speed of 1 ms^{-1} (DPAG 2006). Nevertheless, it would not be able to detect 10^5 Bq ^{60}Co particles at 100 mm depth reliably, should they exist in the environment.

4.4.21 It was noted in the previous COMARE/DPAG report that there are likely to have been particles containing activities of less than 10^5 Bq ^{137}Cs that were not detected by Groundhog Mark 1 over the monitoring period. The present trial has established that Groundhog Evolution 2 can detect particles containing 10^3 and 10^2 Bq ^{137}Cs, albeit with a low probability. Further monitoring using this system may yield data that should permit an upper bound to be placed on the likely number of low-activity particles present.

4.4.22 Whilst no significant differences are observed between Groundhog Evolution and Evolution 2 for 10^5 and 10^6 Bq ^{137}Cs particles to 200 mm depth, as both systems perform reasonably well to this depth, Groundhog Evolution 2 is shown to be capable of detecting 10^6 Bq ^{137}Cs particles to a depth of at least 400 mm and has a reasonably high probability of detecting 10^5 Bq ^{137}Cs particles to a depth of 300 mm. This meets our recommended target requirements of 10^5 Bq ^{137}Cs at depths of in excess of 200 mm (DPAG 2006). In addition, this detection capability provides some reassurance that *significant* and *relevant* particles arriving in a typical sand bar of *c.* 200-300 mm thickness, migrating across the beach between survey periods, have a high probability of being detected.

4.4.23 For 10^4 Bq ^{137}Cs particles, Groundhog Evolution 2 shows significantly improved detection capabilities for all measured depths greater than 50 mm compared with Groundhog Evolution. The system also shows improved detection capabilities for ^{60}Co.

5. Offshore Particles

5.1 Introduction

5.1.1 Our Third Report (DPAG 2006) paid considerable attention to the 929 radioactive particles that had been recovered from the sea bed off the N coast of Scotland up to February 2006. All of these finds had been made by divers during the period from summer 1997 to 2005. The divers recorded the exact location of every find and the depth to which sea bed sediment had to be removed to recover it. The radionuclide composition, activity and nature of each particle were established by examination and counting in UKAEA laboratories after every particle had been brought onshore. A database of all finds and their properties was maintained by UKAEA. In response to comments from DPAG, this database was repeatedly checked for quality assurance by UKAEA, corrected and upgraded where necessary, and was eventually published in full on the UKAEA website (www.dounreay.com/particle-cleanup/particle-finds) and as Appendix I in our Third Report (DPAG 2006).

5.1.2 Our Third Report (DPAG 2006) elaborated a conceptual model of particle behaviour in the offshore environment, and of how particles found on beaches are supplied from a long-lived population on the sea bed. This model implied that without remedial action, particles would continue to contaminate publicly accessible beaches for decades. The removal from the sea bed of high-activity particles that act as a feed-stock by slowly disintegrating to form smaller particles with lesser activities would do much to curtail the duration of the beach contamination. Because the greatest hazard to the public comes from *significant* particles (*i.e.* those with $>10^6$ Bq of ^{137}Cs activity), public safety would be assured if remedial action were based on targeting these and removing them in preference to other particles with lesser activity. DPAG noted that the use of divers is an effective way of accomplishing this.

5.1.3 UKAEA became concerned that the high intensity of diving involved in finding and recovering particles might present overall risks to divers that outweighed the benefits to the public that resulted from reducing the numbers of particles in the environment. More than 1200 dives were carried out in the period between 1997 and 2005 for the purposes of locating and retrieving particles and related offshore research at Dounreay. In 2003, UKAEA commissioned RM Consultants to carry out a desk-based study of the risks associated with commercial diving. Their report (D. Carter *et al.* RMC Report R03-127(T)) concluded that the statistical information required for such an assessment was not available from either of the two principal organisations concerned, the Health & Safety Executive (HSE) or the Association of Diving Contractors (ADC), nor from other diving associations. Diving as an occupation is considered by HSE to be “high hazard” – the fatal accident rate for offshore and inland/inshore sectors being considerably higher than for construction and agriculture. UKAEA in 2003 commenced the testing and development of sub-sea ROV technology which was intended eventually to replace the need to use divers to find and retrieve the particles. Diving for particles was stopped by UKAEA in 2005 and replaced by a temporary ROV mapping programme, described in Chapter 4. It is intended that this mapping in turn will be replaced by robotic retrievals for offshore clean up and research when the technology to do so has been proved. Trials of two robotic retrieval systems took place over the winter and spring of 2007-8, as mentioned in Chapter 4.

5.1.4 DPAG has noted UKAEA's wish to replace diving by using a remotely operated vehicle and welcomed the UKAEA effort to develop a reliable system for targeted retrieval of particles. DPAG has also noted the lack of useful statistical information with relevance to diving risks at Dounreay. Meeting the recommendation in our Third Report (DPAG 2006) for targeted removal of high-activity particles should not be taken to rule out the use of divers in future.

5.1.5 In 2004, the first ROV, named TROL was deployed in trials which were extended in 2005. The TROL was operated from a survey vessel. It consists of a tracked vehicle carrying a marinised gamma spectrometer (for details, see Chapter 4 of this report). In both 2004 and 2005, TROL proved itself capable of detecting particles and establishing the coordinates of their position on the sea bed to a precision of several metres[11]. Some of the "strikes" by TROL were verified by divers to be due to particles. The depth of burial and activities of these particles were included in the database of diver finds as a result. However, the TROL itself could not at that time discriminate between a low-activity particle buried beneath only a shallow depth of sediment, and a higher-activity particle buried deeper.

5.1.6 The 2004 and 2005 TROL strikes were discussed in the our Third Report (DPAG 2006), which noted that they appeared to confirm the approximate seaward limit of the pattern of particle distribution on the sea bed established by divers.

5.1.7 In 2006 and 2007, UKAEA carried out further survey work using the TROL system and commenced development of a new method that would allow the activity and depth of burial of a particle to be deduced. The method is described in Chapter 4 of this report. Though the spectra of 2004-5 have been used retrospectively to calculate depth and activity for each particle strike made in those years, the differences in procedure mean that the calculated depths in particular are very approximate, compared with the calculated data for 2006-7.

5.1.8 ROV surveys since 2004 have made 300 particle strikes and, for 263 of these, the recorded spectra were adequate for estimating their burial depths and activities, on the assumption of a single particle being responsible for

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[11] The Ultra-Short Baseline (USBL) acoustic positioning system has been utilised during many subsea particle investigations at Dounreay to find the position of an ROV (or diver) relative to a surface vessel. A position can be fixed by computing the range and bearing between a vessel-mounted transceiver and a ROV (or diver)-mounted responder. By measuring the time taken for an acoustic signal to transit the ship and ROV a range can be calculated. Bearing is derived by comparing the small differences in the time of arrival of the reply signal at each receiver element within the transceiver. On board the surface vessel, data from the USBL and other sensors such as pitch-and-roll, heading, depth and GPS are corrected and computed. The subsea vehicle's track and surface vessel's position is displayed *via* a hydrographic software package, which is used by a surveyor and ROV pilot to monitor progress. Data can also be interrogated and stored for subsequent analyses.

the radioactivity observed in each strike. The ROV is capable of deployment in deeper water than divers can reach, and this has enabled small areas to be surveyed that are scattered across a much wider region of sea bed than the divers' surveys. Fig. 5.1 shows the distribution of ROV surveys along the whole coast between Strathy Point and Dunnet Bay, together with the outlines of areas that are illustrated at a larger scale later in this Chapter. Taken as a whole, the ROV survey campaigns of 2004-7 had the following aims, in addition to technical development and testing:

- Delineate the main plume of particles that divers' surveys had revealed as extending NE of the Old Diffuser (OD), roughly parallel to the coast. The ROV surveys were aimed in particular at discovering whether the plume extended further towards the NE than had been mapped from diver finds and whether the seaward limit drawn to the NW of the scatter of diver finds is correct. Increasing water depths had limited the coverage provided by divers in both respects, so the ROV had capability for adding data in previously un-surveyed areas.
- Compare the spatial density of particles within the main plume, between diver finds and ROV strikes, to check the diver-based estimates of total particle numbers, as presented in our Third Report (DPAG 2006), and to assess the ROV's overall capabilities by comparing depths and activities of particles found by the two methods at the level of populations.
- Investigate the possible occurrence of particles further afield from the main plume, as far as Dunnet Bay in the E and Strathy Point in the W and to use the results to test the predictions of the Wallingford Model regarding particle dispersal on the sea bed.
- Investigate the area between the OD and the inner parts of Sandside Bay and to improve estimates of particle numbers and activities in this region, which is important as it provides the immediate source of particles that come ashore on Sandside Beach.

5.1.9 The remainder of this Chapter considers the ROV results in detail, in terms of the light they throw on these issues. We also consider the implications of the new results for the general validity of the conceptual model of offshore particles as developed in our Third Report (DPAG 2006), and whether these concepts require updating or revision. The next section, therefore, provides a brief outline of the conceptual model, based on the more detailed treatment in our Third Report (DPAG 2006).

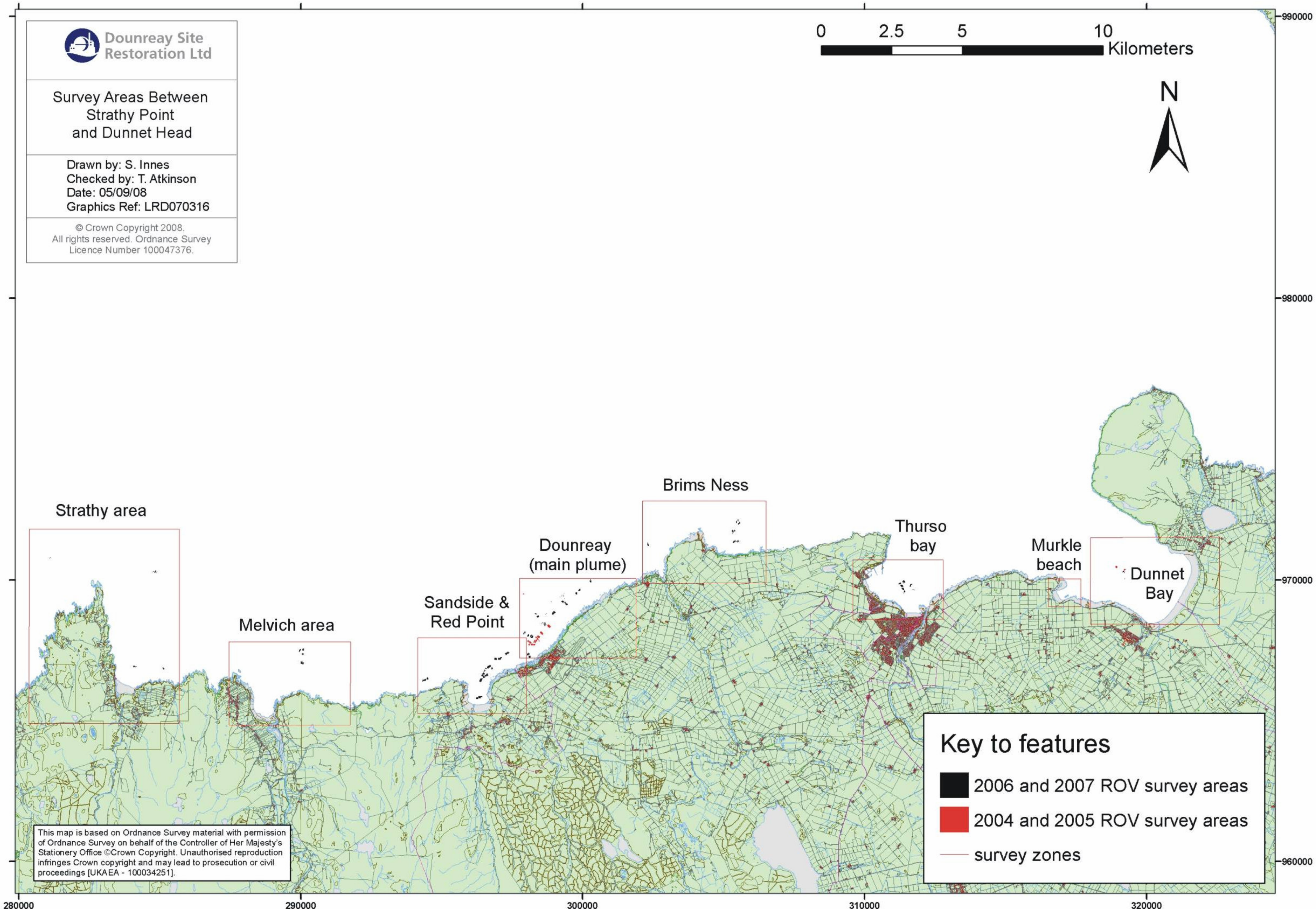

Fig. 5.1 **Survey areas between Strathy Point and Dunnet Head**

5.2 Conceptual Model of Particle Behaviour Offshore

5.2.1 The radioactive particles on the sea bed are distributed in a plume extending NE and SW from Dounreay, with its origin at the OD. Most particles were released in the 1960s and 1970s and the plume has formed by dispersal from these early releases but has also persisted over the decades since. Additional releases *via* the OD might have been possible up to the late 1980s or even the1990s, but it cannot be established with certainty that any occurred. It is also possible that some particles could have reached the sea *via* other routes, but there is even greater uncertainty as to whether significant numbers did so.

5.2.2 The radioactive particles have two principal origins: as milling swarf from MTR and other reactor fuels, and as clinker-like solids formed accidentally during the reprocessing of Dounreay Fast Reactor fuel (DFR particles). Both types of particle have undergone fragmentation and surface attrition in the sea, and most are now in the size range from less than 0.1 mm to several mm, maximum dimension. This is the same size range as natural sand and the Dounreay particles are subject to the same processes, causing suspension and movement, as affect sand grains on the sea bed.

5.2.3 The degree to which the particles differ from sea-bed sediments in their behaviour depends upon their relative size, density and shape. Measurements made since publication of our Third Report (DPAG 2006) show that eleven out of thirteen MTR particles tested had densities between 2.6 and 3.0 g cc^{-1} whereas two MTR and four DFR particles were all denser than 3.1, the upper limit that could be measured by the technique used. Most natural sand grains have density around 2.7 g cc^{-1} (2.65 for quartz, 2.72 for calcite). Denser particles will settle more quickly from suspension in water and it will also be more difficult for currents to set them in motion than the natural sands around them. Differences in shape and size will reinforce the effects of density in causing different behaviour between Dounreay particles and natural sand. Natural sand grains tend to have rather equant shapes in which the minimum and maximum diameters across a particle are similar. The Dounreay particles have shapes that vary with their overall size, being predominantly fairly equant among the smaller sizes, but tending towards platy or bladed shapes among the larger particles (DPAG 2006, pp 38-46). Taken together, these shape and size trends suggest that the smaller particles among the MTR population will be mobilised and transported in much the same way as natural sands, especially if they are of similar density, whereas larger and/or denser MTR particles and all DFR particles will require larger water velocities to move them than would be needed for sand grains of equivalent size.

5.2.4 Dounreay particles will tend to be buried beneath the surface of the sediment during calm weather when water velocities are enough to shift natural sand but are too slow to move particles that are significantly larger or denser or different in shape. In storms, wave velocities may be enough to suspend much of the surface layers of sand within the water column. When this happens, the larger, non-equant, or denser Dounreay particles will settle at different rates from the natural sand as currents wane, and suspended material returns to the sea floor. Denser and larger particles will settle faster, leading to a tendency for them to be buried by slower-settling, natural sand. Non-equant grain shape will have the opposite effect, although possibly insufficient to cancel out the influences of size and density. The overall effect is that many MTR and probably all DFR particles will tend to be buried following storms, while the smaller and less dense among the MTR particles will move with the sand around them during both stormy and calm weather.

5.2.5 There is a broad correlation between the ^{137}Cs activities of particles and their mass. This is fortunate, because activity is the only property that has been measured for every particle. It can be used as an imperfect surrogate for particle size. There is also a slight tendency for activity to increase with density among the thirteen MTR particles measured.

5.2.6 The particles that were originally released from the OD have been moved by the combined effects of tidal currents and waves. The natural sands on the sea bed are moved quite frequently by tidal currents alone, and the smaller MTR particles can be transported with them. The tides have a two-way motion, moving sand first in one direction on the flood tide and then back again on the ebb. These opposing motions do not exactly cancel one another out, and over much of the sea bed off Dounreay there is a small residual current that tends to transport sand parallel to the coast. This residual current passes to the NE, and this is responsible for the plume of smaller (*i.e.* lower activity) MTR particles that runs NE from the OD and extends along the coast at least as far as Dunnet Bay. However, there is a narrow band of sea bed close to the rocky sub-shore just SW of the OD in which the tidal residual current carries sand in the opposite direction, *i.e.* SW. This transports smaller MTR particles from the area inshore of the OD towards Sandside Bay and beyond.

5.2.7 The larger and denser Dounreay particles require higher velocities to initiate their motion than can be supplied by tidal currents alone. Under calm conditions they will tend to remain stationary and become buried by any natural sand that is moving. When tidal currents are at their most rapid these particles may roll or slide, but will do so much more slowly than the movement of natural grains around them. However, the extra currents produced by large waves are on occasion enough to shift even the largest and densest of the Dounreay particles. The water at the sea bed oscillates back and forth as each wave passes overhead, but there is a net movement in the direction in which the wave is travelling. The higher the wave, the deeper the water motions extend, and the faster are the oscillating currents at any given depth. The largest Dounreay particles will require fairly large waves to move them, and these occur much less frequently than smaller waves. Thus the large, high-activity particles will be moved only during big storms, whereas lesser particles will be moved more often, and thus can be expected to travel further over a given period of years.

5.2.8 The coastlines of the mainland and the islands of Orkney exert a strong influence on particle movement by waves. They block the generation of waves by winds from any quarter except between W and NNE. Waves generally run in the same direction as the winds that produce them, but they are deflected by the shore as they approach the coast. This causes the waves in shallow water to transport particles parallel to the shore. The coast close to Dounreay runs from SW to NE, so that when the wind blows from directions between W and NW the resulting shallow-water waves transport the larger, more radioactive particles NE. The plume of particles extending in this direction contains high-activity particles to distances of up to 2 km from the OD but most are within one km. In contrast, very few high-activity particles have been transported in the opposite direction and all lie within two hundred metres of the OD. The reason is that moving large particles in this direction requires winds to blow from between NW and NNE. These winds are less frequent and usually less violent, so their cumulative effect on transport is less than that of the opposing Westerlies. Thus the net effect of wind-induced waves is to transport larger, higher-activity particles predominantly NE, but at slower rates than the small particles that can be moved by tidal currents alone.

5.2.9 Another effect of waves is to drive particles towards the shore. This is the reason that the plume lies towards the landward side of the OD, and also the reason that particles are transported from the sea bed onto Dounreay Foreshore. Waves are probably also responsible for driving particles into Sandside Bay from the plume travelling SW from the OD.

5.2.10 Taken together, the combined effects of tidal currents and wind-induced waves provide a rational explanation for the shape of the particle plume, and for all the differences between particles of different sizes, as reflected in practice by their higher or lower levels of radioactivity. The relatively more efficient transport of small particles means that they predominate at greater distances from the source at the OD.

5.2.11 The persistence of the plume through several decades since the main releases of particles from Dounreay can be accounted for by considering the effects of burial. Once buried, a particle is no longer available to be moved until the bed is scoured by waves down to the level at which it lies. When conditions are fairly calm, moving sand will tend to bury the particles that are too large or too dense to be moved by tidal currents alone. More importantly, storm waves have been shown to disturb parts of the sea-bed sediment down to depths of half a metre or more. When a storm disturbs the bed, the larger denser particles that are lifted into suspension will fall back faster than the natural sand and will be buried when the bed settles. Large waves scour the bed more deeply than small ones, so the bigger the storm, the more deeply will it mobilise the sediment, and the deeper will some of the particles be buried as a result. Large waves on the Dounreay coast only result from storms with prolonged high winds blowing from between W round to NNE. Because bigger storms occur less frequently than more moderate ones, large waves are also less frequent. When they do occur, they bury many of the particles at depths where they may remain undisturbed for a long time. All sizes of particles will be buried, but the larger and denser ones will be affected preferentially. In addition to these physical movements there may also be vertical transport of particles within the sediment through bioturbation. Overall, periodic burial and reburial greatly slow down the rate of transport, compared with surface sand and those small Dounreay particles that happen to be present at the surface.

5.2.12 All of these processes are illustrated in diagrammatic form on Fig. 5.2, which employs a notation of boxes to signify the different parts of the main plume, the beaches and shore, and the sediment in which buried particles are stored in an immobile state. The picture is not complete, however, without taking into account one further process, which is the effect of fragmentation. It is known that all types of Dounreay particles undergo fragmentation, probably as a result of physical cracking and weakening due to electro-chemical corrosion by sea water, followed by stresses imposed by movement. The average lifetime of a particle between fragmentation events is estimated to be between six and seven years, and the largest fragment produced contains on average 80% of the radioactivity. Thus, large particles are occasionally breaking up to produce slightly smaller particles, which in turn break up to produce smaller particles still, and so on. Recalling that the smaller particles are transported much more efficiently, whereas the larger ones move at a slow average rate, one can envisage that the longevity of the plume must be due to burial of the largest, most radioactive particles in the sediment. When re-mobilised, some of these buried particles will break up and produce somewhat smaller particles, many of which will be reburied in turn. Only the smallest particles will be easily transported away from the central area of the plume. Over time the activity of the largest particles that remain near the origin of the plume should slowly reduce as more and more of them have undergone several break-up events and their radioactivity also decays. The smaller, less radioactive particles which are generated by this break-up will replace those that have been transported away to the more distant parts of the plume, thus maintaining the plume's overall longevity.

5.2.13 The very smallest particles will eventually be fragmented down to silt size. This will produce a marked change in their transport, as silts remain in suspension in a turbulent sea for far longer than sand grains and so can be transported over large distances quite rapidly. The original particles released at the time of the plume's origin may have been of all sizes, but only the largest from that time remain near the OD. Possibly all of the smaller original particles have been reduced to silt and removed from the area altogether, but these smaller sizes have been replaced, maybe several times over, by fragments generated from the larger and medium-sized particles. Through this combination of transport, burial and fragmentation, it appears that the plume may have remained in a quasi-steady state over a long period. If no further intervention is undertaken, it may take several more decades before the gradual decline in activities and physical size will have eliminated all of the *significant* particles, but this process could be speeded up by targeted removal of the larger buried particles that constitute the feedstock of the plume.

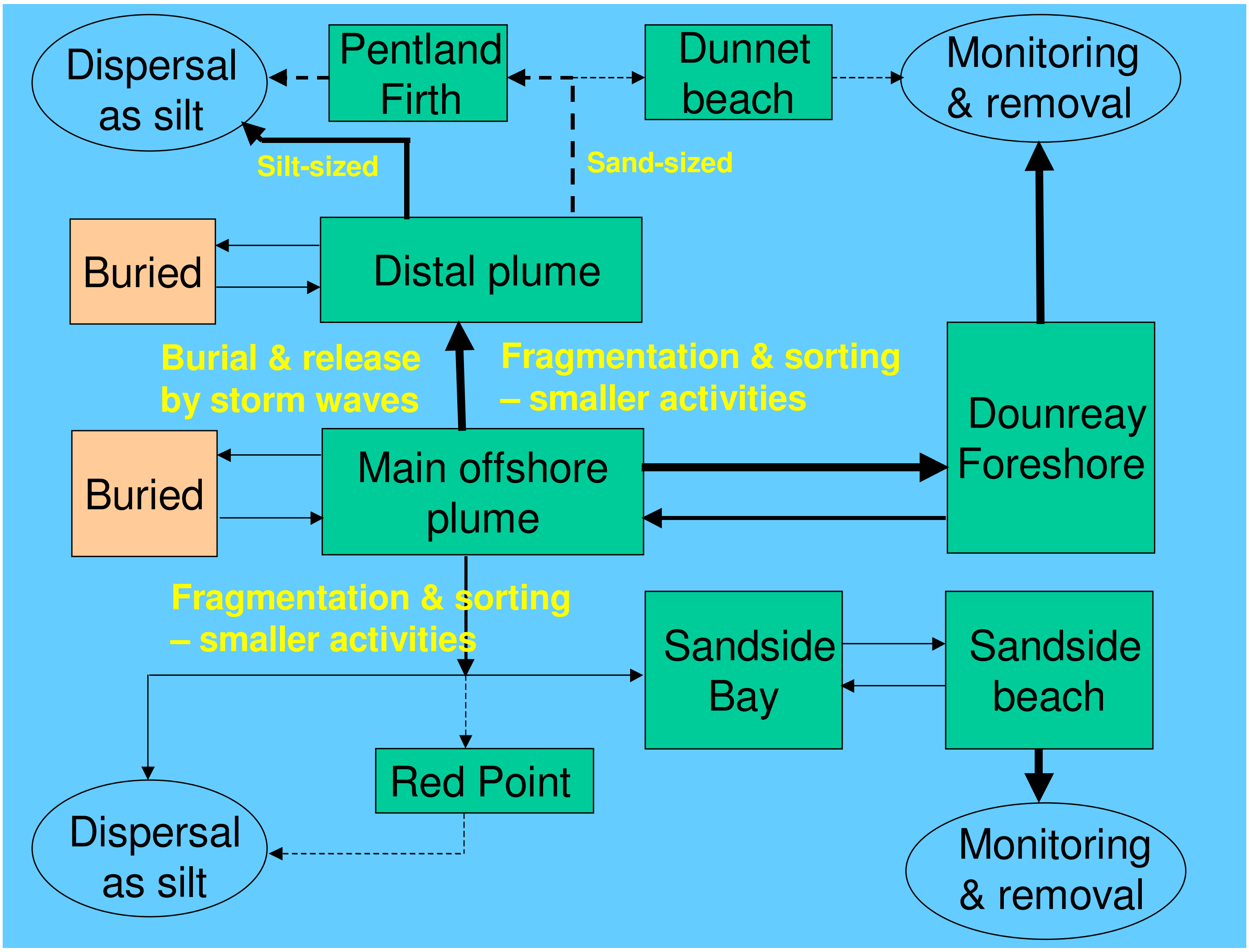

Fig. 5.2 A conceptual model of Dounreay particle transport

Rectangular boxes indicate accumulations of particles; arrows show exchanges between them that take place due to the action of tides, wind and waves. Large text in yellow indicates processes affecting the particles. Oval boxes indicate ultimate sinks for particulate radioactive material, once reduced to silt size, or if recovered from beaches.

5.3 The ROV Surveys of 2004–7: Evaluation of Particle Locations

5.3.1 Fig. 5.1 shows the spatial distribution of small patches of sea floor that have been searched for particles by the ROV in the years 2004–7. A widespread coverage along 40 km of coastline was achieved, from Strathy Point 15 km W of Dounreay to Dunnet Bay, 25 km E. This coverage has been broken down into seven areas, as indicated by enclosing frames on Fig. 5.1. New particle strikes were made by the ROV in only three areas – Sandside & Red Point, Dounreay (main plume), and Brims Ness. However, beach surveys found a particle on Murkle Beach in 2007, immediately W of the Dunnet Bay area. No particles were located during ROV surveys of the Strathy, Melvich or Thurso Bay areas.

5.3.2 Rather than dealing with the ROV particle locations on an area-by-area basis, they will instead be discussed in terms of the points listed at the end of the introduction to this Chapter (section 5.1). Leading on from this, the question of whether the conceptual model of particle behaviour developed in our Third Report (DPAG 2006) now requires modification will be discussed in section 5.3.7.

The Main Plume (Dounreay Area)

5.3.3 Fig. 5.3 shows the location of diver finds and ROV strikes on the sea bed off Dounreay, with an enlarged inset of the area close to the OD. The spatial pattern of particle locations can be assessed from these data, but the immediate visual impression that they provide should be treated cautiously. The search patterns used during diving were not wholly systematic. Most areas were searched only once whereas some, the 'repopulation areas' (see DPAG 2006, 4.4.30/31) were cleared of all particles, then searched again on several later occasions. These areas are shown by circles on Fig. 5.3. In addition some of the ROV survey areas were located with a deliberate bias to the seaward and distal edges of the plume, whereas others were deliberately located in areas with higher-than-average spatial densities of divers' finds. Thus, the visual impression of spatial locations of particles given by Fig. 5.3 may be quite distorted relative to the true pattern. To overcome this problem, a methodology was used in our Third Report (DPAG 2006) that attempted to correct the bias caused by patchy non-random searching by divers, and remove the influence of multiple searches in 'repopulation areas'. A grid of 100 m x 100 m squares (1 hectare squares) was set up, based on the National Grid, and every find was assigned to the square in which it occurred. The total number of particles likely to be present in every square was then estimated by dividing the actual finds for that square by the proportion of its area that had been searched. This procedure provided an estimate of the total population of particles in every one-hectare grid square. Many squares were not searched, but for those that had been, an estimate was made of the likely error in the number of particles, based on numbers found. Finally, the pattern of distribution of gridded estimates was contoured by hand, with allowance being made for the probable reliability of values for individual squares, and attention being paid to the notion that the true distribution pattern was more likely to have a smooth variation of numbers across the sea bed than an abruptly varying, discontinuous layout of particle densities. Separate contour maps were prepared for *significant* and *relevant* + *minor* categories, because these groups had been demonstrated to have distinctly different burial patterns. (These maps were shown in our Third Report (DPAG 2006) as Figs 4.20 and 4.22.)

5.3.4 A similar methodology has now been adopted with the ROV strikes of 2004–7. First, each strike was classified as *significant*, *relevant* or *minor* on the basis of its modelled ^{137}Cs activity[12] There is some evidence that the ROV model overestimates the true activity, so this procedure may slightly overestimate the proportion of total strikes that are *significant*. In terms of assessing risk to the public, this bias is precautionary in its effects. Every strike was assigned to a one-hectare grid square, on the basis of the coordinates of its position as determined by UKAEA from the diving vessel's

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[12] Thresholds between the classes are 10^6 Bq and 10^5 Bq, as in our Third Report (DPAG 2006).

global positioning system (GPS) and the ROV's positioning system relative to the vessel. This gave numbers of *significant* and *relevant* + *mino*r strikes for every grid square that had been partly searched by the ROV. Total numbers per square were estimated by dividing the numbers of strikes by the proportions of the square searched. No attempt was made to allow for the proportion of buried particles that remained undetected by the ROV, because there is insufficient knowledge of its performance and detection efficiency. In our Third Report (DPAG 2006), this correction increased the numbers of *relevant* + *minor* particles by factors of 1.1 to 1.5, depending on water depth. The correction factors were based on a statistical analysis of the activities of particles recovered from the uppermost 100 mm of sediment, having first classified the finds according to water depth. Because most of the ROV strikes are in water deeper than 20 m, the correction factor of 1.5 is the one from our Third Report (DPAG 2006) that is most likely to apply. However, it may still be inappropriate because many of the ROV areas are in deeper water than any area searched by divers, so there are no previous finds on which to base a statistical correction. Because of these uncertainties, it was decided not to correct the ROV estimates for burial effects. It should be borne in mind that the grid square estimates mapped in our Third Report (DPAG 2006) were similarly uncorrected, but that corrections were applied to estimates of total numbers of particles in the plume as a whole, bearing in mind the proportions found beneath various depths of water.

5.3.5 Fig. 5.4 shows the 100 m x 100 m grid, with ROV-based estimates of numbers per square, *plus* diver-based estimates for those squares surveyed by both methods.

5.3.6 The outer limits of the main plume were mapped in our Third Report (DPAG 2006) using contours of one particle per hectare for *significant* particles and five per hectare for *relevant* + *min*or. These contours are reproduced in Fig. 5.4. The ROV surveys included areas (marked V, X and W) on the projected line of the axis of the mapped plume, but beyond its mapped limits. These areas did not give rise to any ROV strikes, suggesting that the previously mapped distal limit of the plume in the NE requires no alteration. Spatial densities of particles beyond the end of the mapped plume are likely to be low.

5.3.7 A greater number of ROV areas are located to the NW, on the seaward side of the main plume. These include areas inside the mapped plume boundaries, where quite large numbers of strikes were expected, and also other areas just within and just outside the mapped edge of the plume. In addition, some areas are located in deeper water beyond the 30 m depth contour; well outside the plume boundaries as mapped in our Third Report (DPAG 2006) (see Fig. 5.4). On the seaward side of the plume, the ROV located a scatter of particles outside the boundary contours, for both *significant* and *relevant* + *minor* categories. On the basis of the estimates for 100 m x 100 m squares, revised contours were drawn that broadened the central part of the mapped plume to seaward. These are shown in Fig. 5.5 for *significant* particles, and Fig. 5.6 for *relevant* + *minor* particles. The changes to the previously mapped plume are slight, consisting of a straighter boundary on the NW side for *relevant* + *minor* group, and an extension of the area N of the OD with more than one *significant* particle per hectare. The basic pattern of the plume remains unaltered from our Third

Report (DPAG 2006), with transport and dispersal being predominantly to the NE. The ROV results do not require any fundamental revision to be made to the model of NE transport of a majority of particles by a combination of tide- and wave-induced currents.

The Distal Plume NE of Dounreay (Brims Ness, Thurso Bay and Dunnet Bay Areas)

5.3.8 In 2006 and 2007, new areas of seabed on the E and W sides of the Brims Ness headland were surveyed by ROV. Previous diving surveys had located small clusters of *minor* particles off Crosskirk Bay, W of the headland, and near the village of Brims Ness on the E side of it. A computer model of particle dispersal, the Wallingford Model described in Chapter 4 of our Third Report (DPAG 2006), had predicted that concentrations of particles might be trapped by gyre-like circulations of marine currents produced by tidal flows around the headland. All these features are shown together with the ROV survey areas in Fig. 5.7. Areas close to the predicted particle concentration NE of the headland were searched in both years but no particles were found. However, three *minor* and three *relevant* particles were located to the S of this area, close to where five *minor* particles had previously been found by divers. These finds confirm that particles are persistently present on the sea bed near Brims Ness, and confirm the existence of a thinly-populated extension of the main plume for at least 8 km along the coast to the E of Dounreay.

5.3.9 No particles have been located on the sea bed to the E of the area just described, despite quite extensive searching of the central part of Thurso Bay (Fig. 5.8), and a smaller search area in the centre of the mouth of Dunnet Bay (Fig. 5.9). However, a single *minor* particle was found on Dunnet Beach in 2005, and a second *minor* particle on Murkle Beach in 2007. These finds confirm that the overall plume extends at least 25 km E of Dounreay.

5.3.10 The new finds made during 2006–7 on the sea bed and Murkle Beach all fit the general pattern of dispersal described in our Third Report (DPAG 2006). Although the modelled activities of three of the ROV finds near Brims Ness place them in the *relevant* category, most of the distal finds have been *minor* particles. Few *significant* finds have been located more than 1 km NE of the OD, and none more than 2 km. Only lesser activity particles, which are probably smaller in size also, have been transported into the more distal parts of this 25 km long plume.

Particles on the Sea Bed between the OD and Sandside Bay (Sandside & Red Point Area)

5.3.11 Fig. 5.10 shows the location of ROV strikes and diver finds on the sea bed between Sandside Beach and the OD (which is located 100 m beyond the E boundary of the map). On the basis of the diver finds and the areas of sand and rock on the sea floor, our Third Report (DPAG 2006) described a plume or train of particles occupying a narrow band parallel to the shore W of Dounreay and turning S into Sandside Bay. Particles have been recovered from all parts of Sandside Beach, so the plume broadens within the bay to feed the whole width of the sandy beach at the bay's head. The total area of this plume was estimated in our Third Report (DPAG 2006) as 68 hectares.

5.3.12 The 2006 and 2007 ROV surveys were deployed to estimate particle distributions and spatial densities in three parts of this plume – the inner bay where a total area of 1.26 ha was surveyed, the sand-floored outer bay which is separated from the inner by outcrops of rock (2.75 ha), and the shore-parallel train of particles running WSW from the main plume near the OD (3.23 ha). On the basis of divers' finds alone, the spatial density of particles in the whole 68 ha plume was estimated in our Third Report (DPAG 2006) as 0.7 particles per hectare, leading to a very rough estimate of 50 – 100 particles being present altogether. The ROV surveys provide new data that imply a larger particle population is present. The spatial density of ROV strikes is five per hectare in the inner part of the bay, three per hectare in the outer bay, and four per hectare in the axis of the plume between the OD and the mouth of the bay. The average density for the whole surveyed area is 3.8 particles per hectare. As the plume area indicated by ROV surveys is much the same as previously mapped using divers' finds, the total number of detectable particles can be estimated as approximately 258. All the finds made so far have been *relevant* or *minor* although the predicted activity of the most active particle located by the ROV is only slightly below the *significant* threshold at $8x10^5$ Bq ^{137}Cs. By comparison with the deep-water parts of the main plume, the factor required to allow for undetected particles buried in the sediment is likely to exceed 1.5. A higher value is possible as the activities of W particles are in general less than in the main plume, so greater proportions will be undetectable when buried to any given depth. A value of two was employed in our Third Report (DPAG 2006) to obtain the upper bound of the 50 – 100 range quoted above for the possible population of particles in the W plume. Using the ROV data, a burial factor of 1.5 would give a total population estimate of approximately 388, while a factor of two gives an estimate of approximately 516. Thus, the likely population of particles between the edge of the main plume and Sandside Beach should now be revised upwards from the 50-100 of our Third Report (DPAG 2006), to 400 – 500.

5.3.13 This new estimate is a considerable increase on what was previously thought to be the population, but the general form of the plume as mapped from divers' finds and ROV strikes still suggests that the conceptual model of particle transport in our Third Report (DPAG 2006) is substantially correct. When the wind blows strongly from the N or NNE there is a component of wave transport W along the coast that is large enough to outweigh the tendency of tidal currents to transport particles NE. Probably, individual particles are moved SW during periods of N winds, then transported NE again by tides in calmer conditions, and by tides *plus* waves when the wind blows from the W or NW, which it does more frequently than it blows from the N or NNE. The W progress of the largest particles (which are likely to be the most active) may be inhibited by the low frequency of N waves that are large enough to move them, compared with the higher frequency of NW waves. However, once a particle has reached the mouth of Sandside Bay the coast provides shelter from Westerlies, whereas NW and N waves will tend to drive the particle into the more sheltered waters of the bay itself. These effects may be responsible for sorting by size, with only smaller particles being transported W, these moving at a slower net rate than their counterparts in the NE trending main plume.

Particles on the Sea Bed W of Sandside Bay

5.3.14 Fig. 5.10 shows the location of a single *minor* particle that was located by the ROV off Red Point, the W headland of Sandside Bay. So far, this is the only particle to be found W of Sandside Bay. The Wallingford Model predicts that sand particles should be transported W along the coast from Sandside, and the presence of this ROV strike confirms that such transport does occur. However, this model also predicts that sand grains derived from Dounreay should be found scattered thinly across the sea bed as far W as Strathy Point. Fig. 5.1 provides an overview of the ROV coverage across this area, and Figs 5.11 and 5.12 show the surveyed areas at a larger scale. The fact that Dounreay particles have not been found here should not be taken to indicate that none exists. The proportion of this very large area that has been surveyed is very small, and the Red Point strike indicates that particles could have entered this W region. Nevertheless, the negative results suggest that any particles that are present are spread across the sea bed at even lower spatial densities than in the E plume. The extension of the latter plume beyond the Brims Ness area has been proved by particle finds on beaches, not on the sea bed.

5.4 Re-assessment of Particle Numbers using ROV Data

Comparison of Spatial Densities of ROV Strikes with Results Presented in our Third Report (DPAG 2006)

5.4.1 The ROV has been used to survey 43 distinct areas within the region of sea bed around the main plume, these are shown in Fig. 5.3. In our Third Report (DPAG 2006), the diver data were generalised by assigning every find to a 1-hectare grid square, and estimating the total number of particles likely to be present per hectare of sandy sediment within every square. These data were then contoured to produce the contour patterns shown in Figs 5.5 and 5.6. for *significant* and *relevant* + *minor* categories respectively. (Figs 4.20 and 4.22 of our Third Report (DPAG 2006) provide the original contour patterns.) Comparing the ROV and diver data in terms of spatial density provides a means of checking the procedures used in our Third Report (DPAG 2006), and of independently assessing the likely accuracy of the estimates of particle numbers present on the sea bed.

5.4.2 The basis of this check is the assumption that the ROV has roughly the same sensitivity and efficiency in finding particles as the diver searches. Slight differences in sensitivity between the two methods were demonstrated in Chapter 4 (section 4.2.6), including a reduced ability to detect near-surface particles by the ROV procedures. These differences should be kept in mind when interpreting the following discussion.

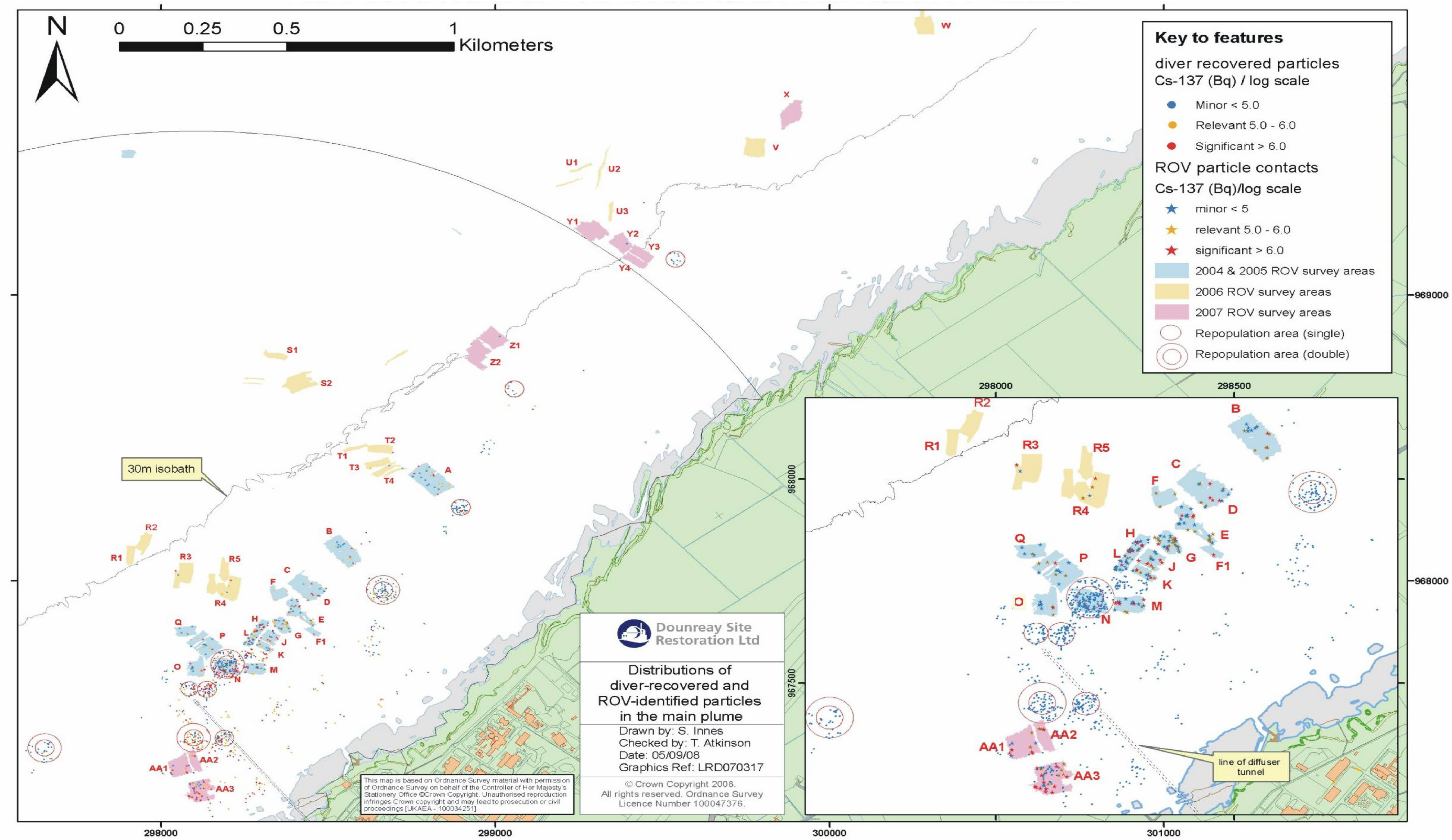

Fig. 5.3 **Distributions of diver-recovered and ROV-identified particles in the main plume**

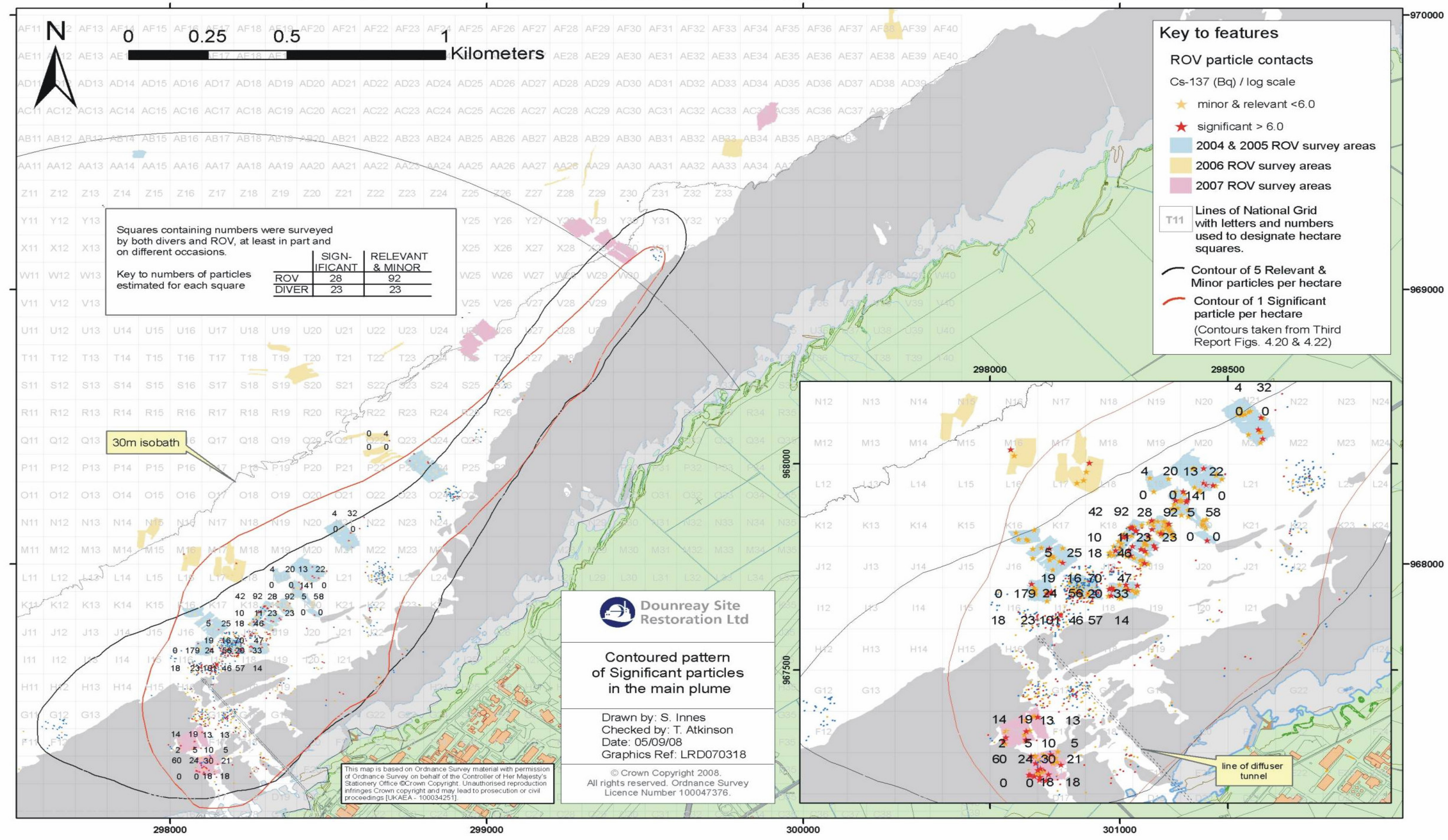

Fig. 5.4 **Contoured pattern of five *relevant* plus & *minor and* one or more *significant* particles per hectare**

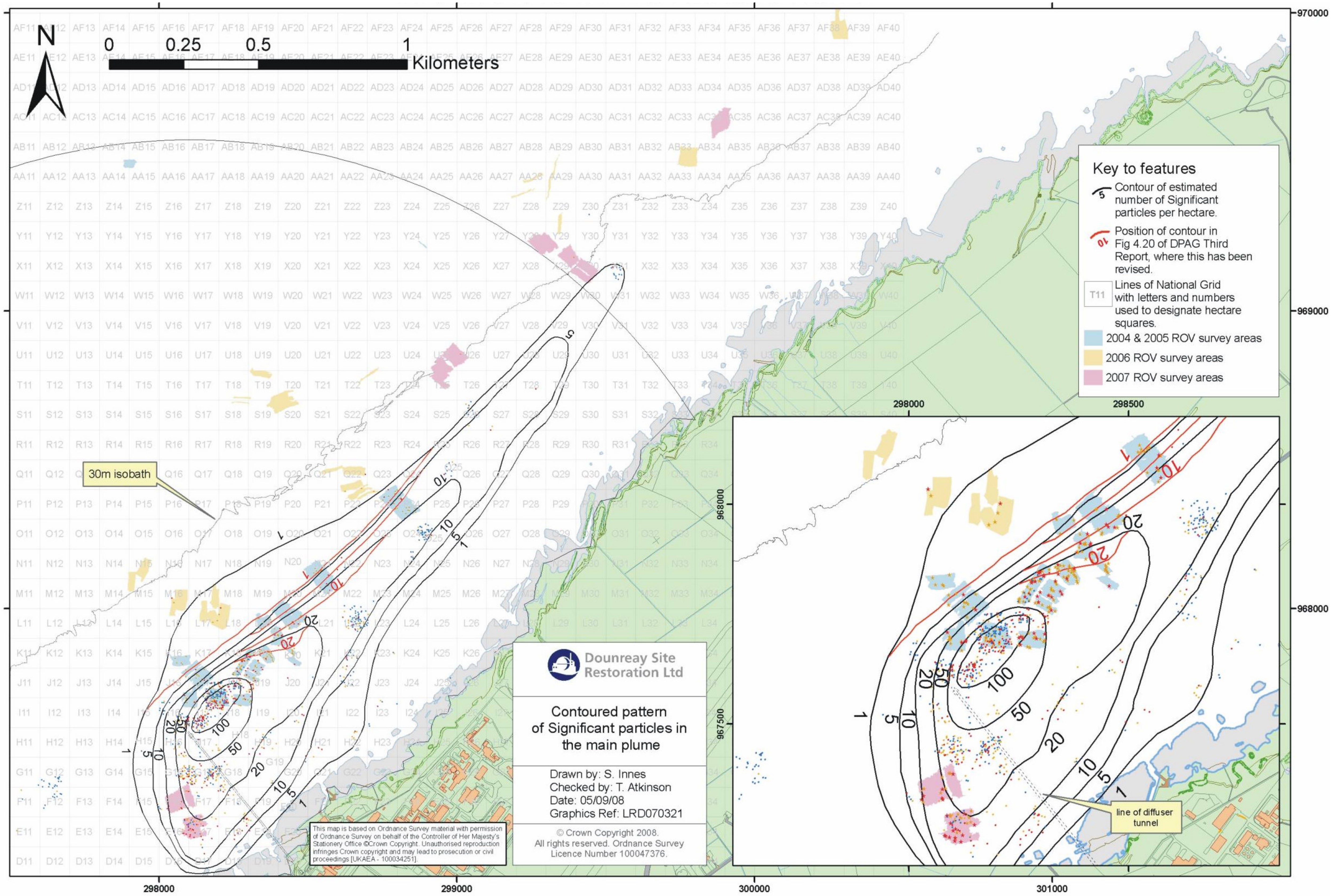

Fig. 5.5 **Contoured pattern of *significant* particles in the main plume**

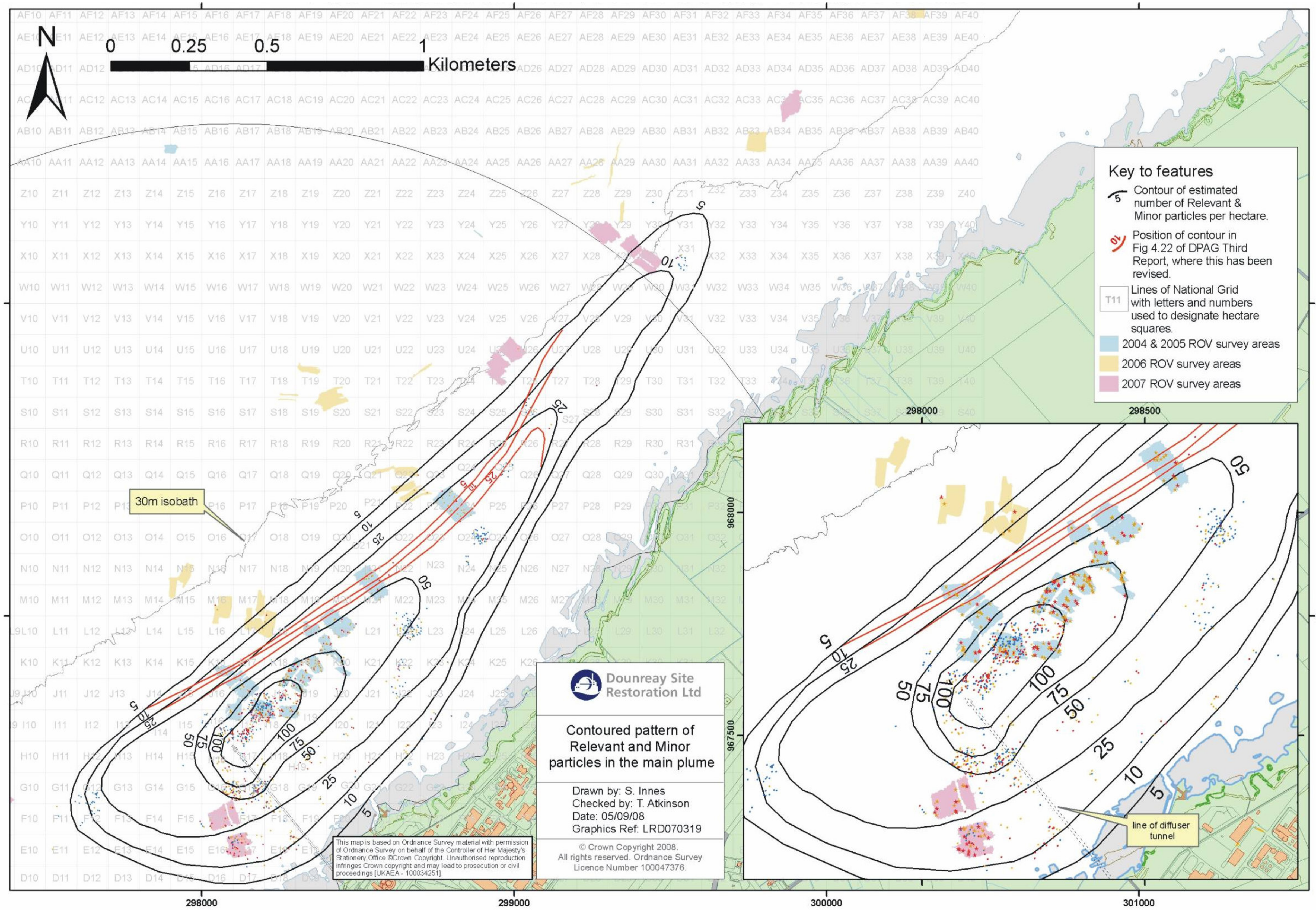

Fig. 5.6 Contoured pattern of *relevant* and *minor* particles in the main plume

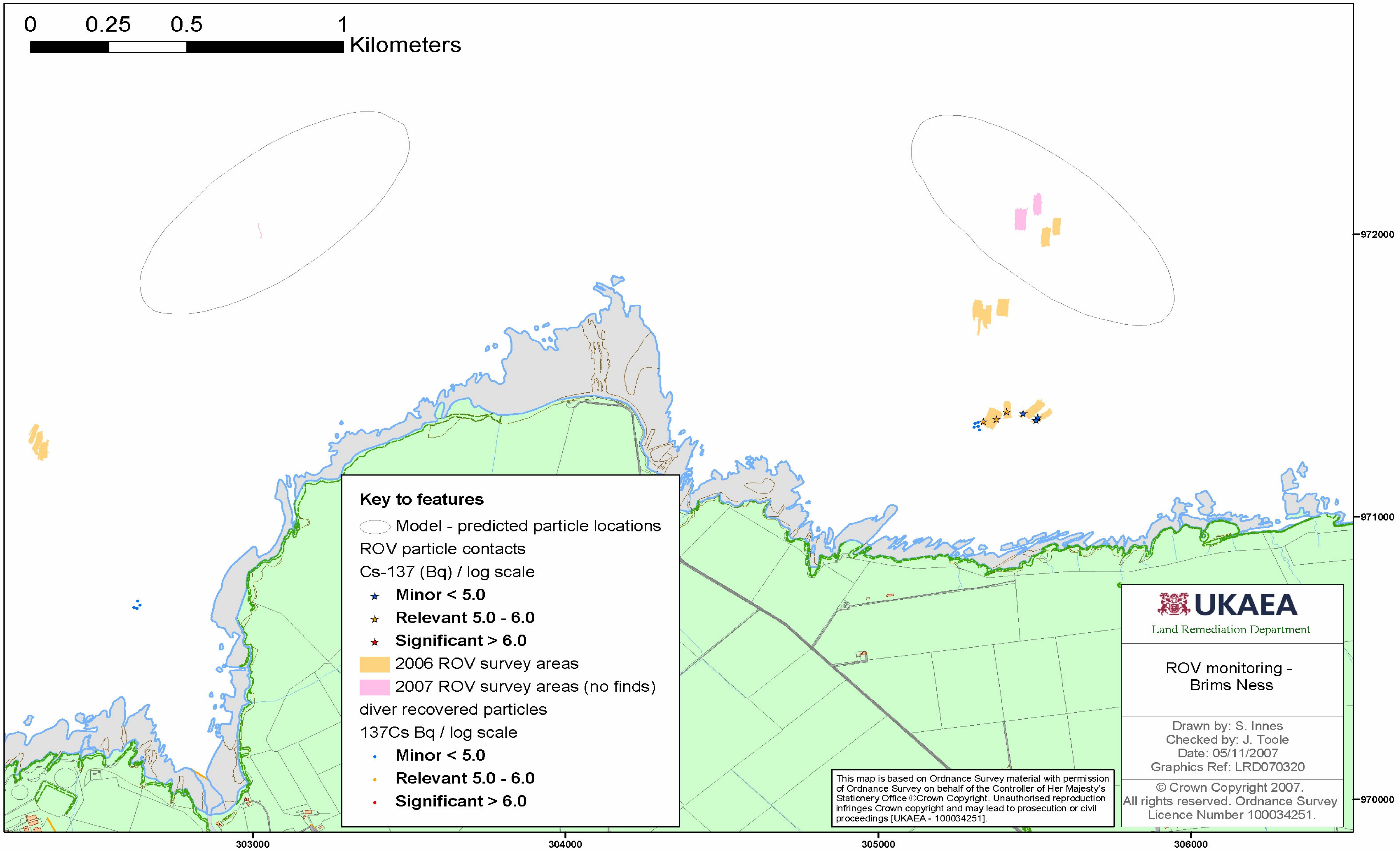

Fig. 5.7 ROV monitoring – Brims Ness

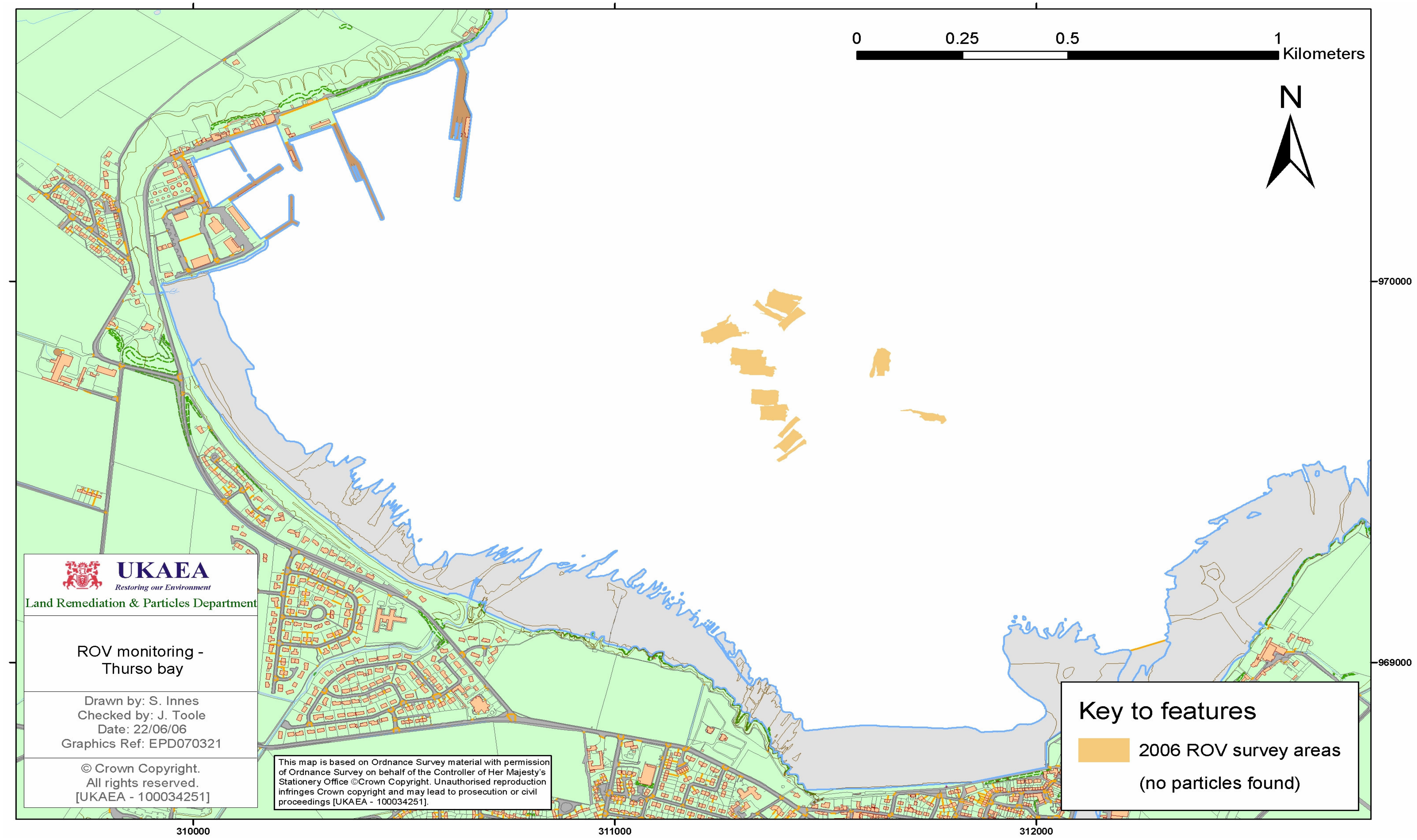

Fig. 5.8 **ROV monitoring – Thurso**

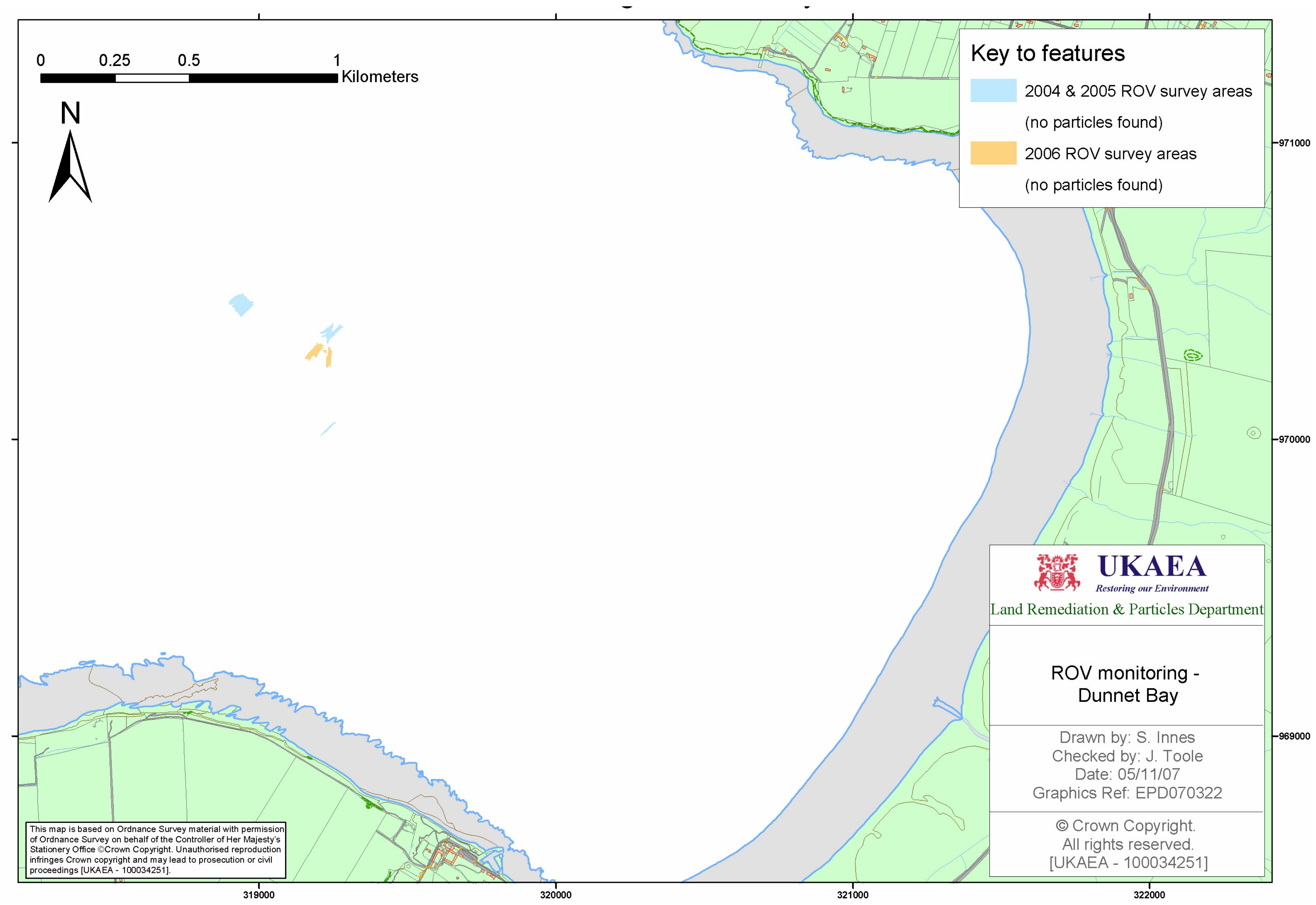

Fig. 5.9 **ROV monitoring Dunnet Bay**

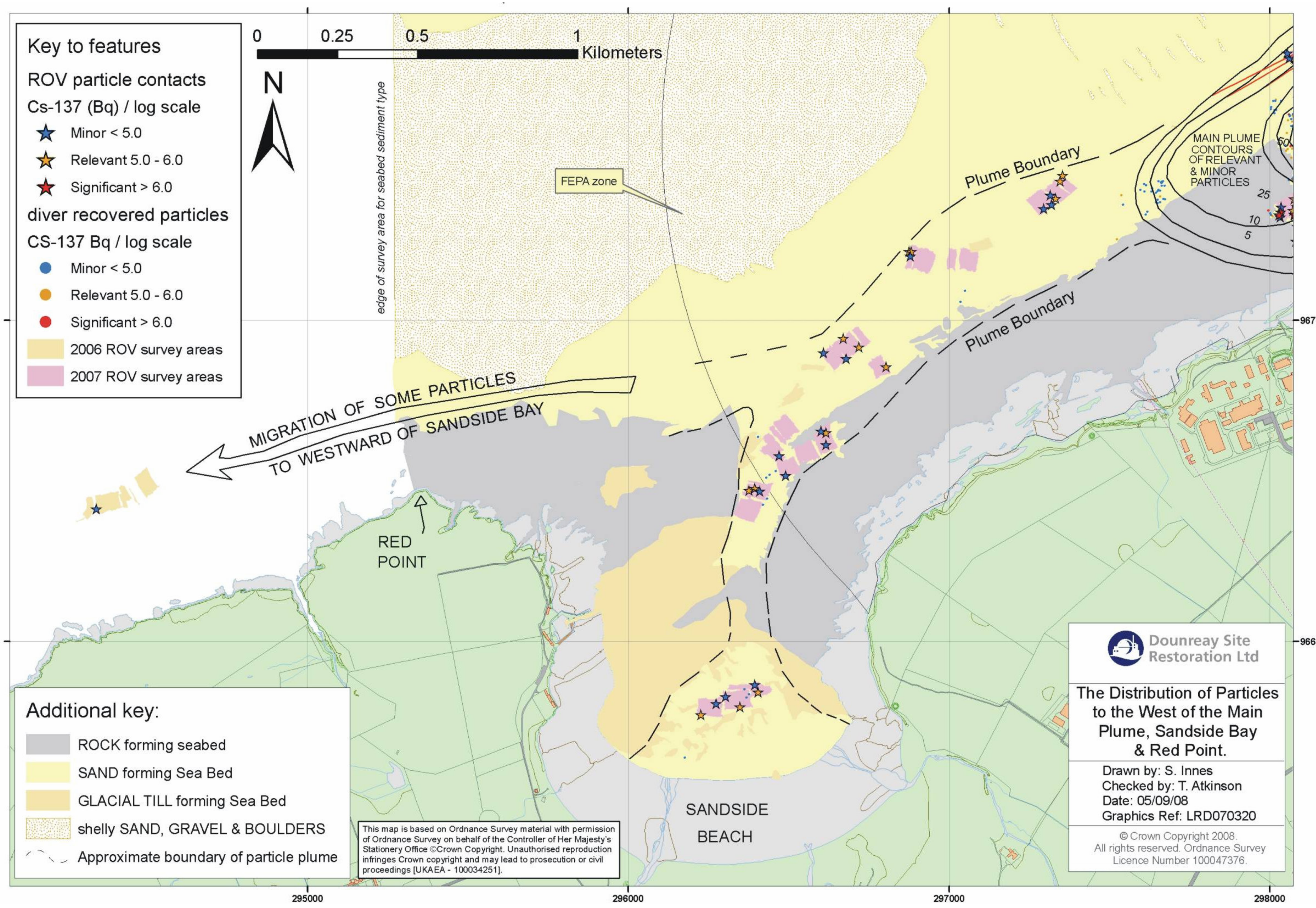

Fig. 5.10 The distribution of particles to the W of the main plume, Sandside Bay and Red Point

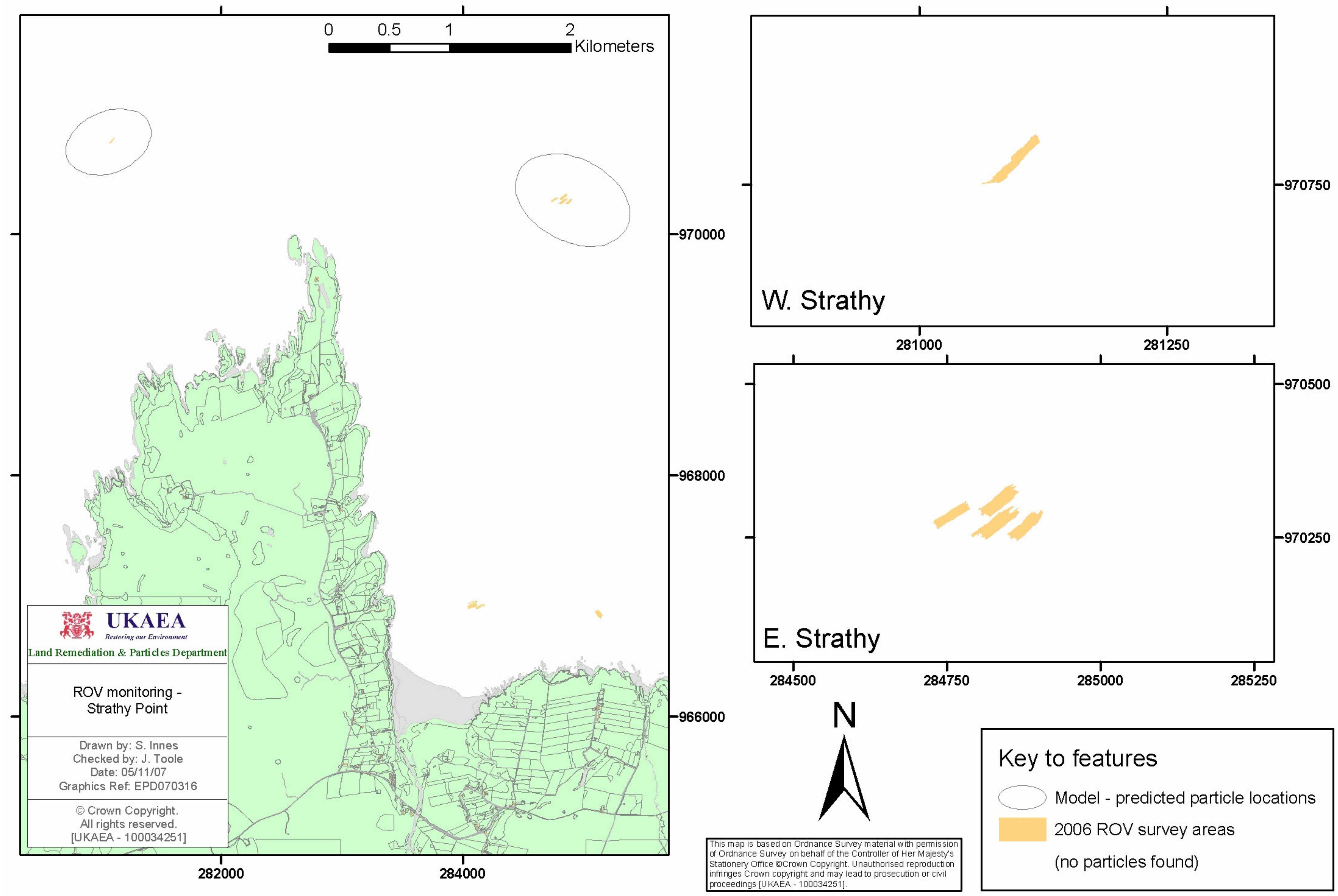

Fig. 5.11 **ROV monitoring Strathy Point**

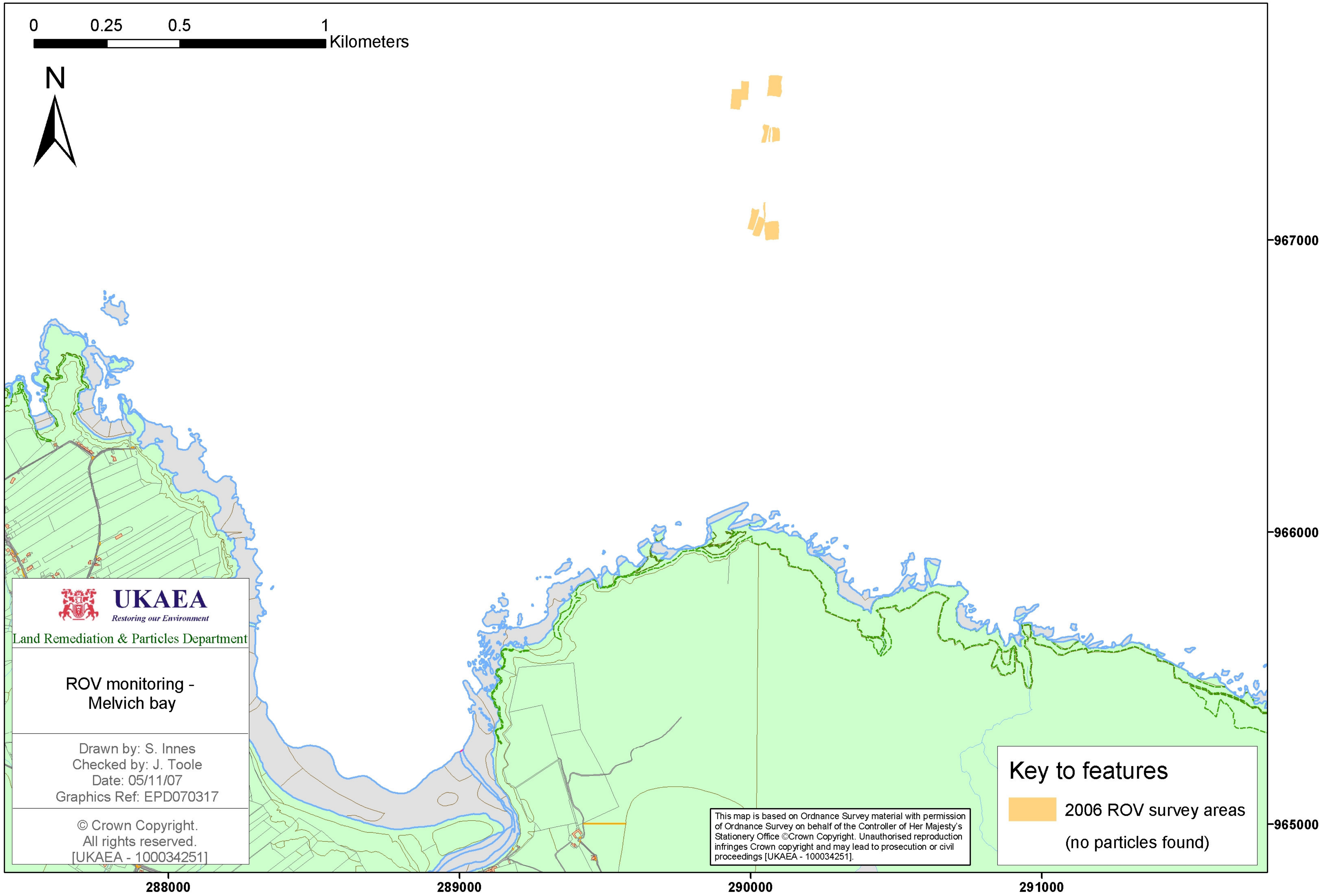

Fig. 5.12 **ROV monitoring – Melvich Bay**

5.4.3 ROV strikes were first separated into *significant* and *relevant* + *minor* groups, on the basis of their predicted activities (DPAG 2006, p. 28). For every category, the spatial density of particles was found for all of the 43 individual survey areas by dividing the number of strikes by the area surveyed. The value thus obtained applies to the area concerned. In Fig. 5.13(a) the ROV values for *significant* particles are plotted against the particle spatial densities predicted by the contour patterns in our Third Report (DPAG 2006), by interpolating between contours to the centroid of each area. The areas are distinguished according to whether they lie fully within the boundaries of the plume as mapped in our Third Report (DPAG 2006), or are located outside the mapped plume. The majority of both types scatter symmetrically around the 1:1 line, demonstrating broad compatibility between the ROV surveys and the previous mapping based on diver finds. However, there are large discrepancies for areas near the centre of the mapped plume, *i.e.* where the greatest numbers of diver finds were made. Two areas (H & AA3 on Figs 5.3 and 5.13(a)) had somewhat larger spatial densities of ROV strikes than would have been expected from the contoured diver finds. In contrast, areas K, O, M & N all showed much smaller densities of ROV strikes than predicted. These discrepancies suggest that the distribution of particles remaining on the sea bed may be more irregular than the contour patterns suggest.

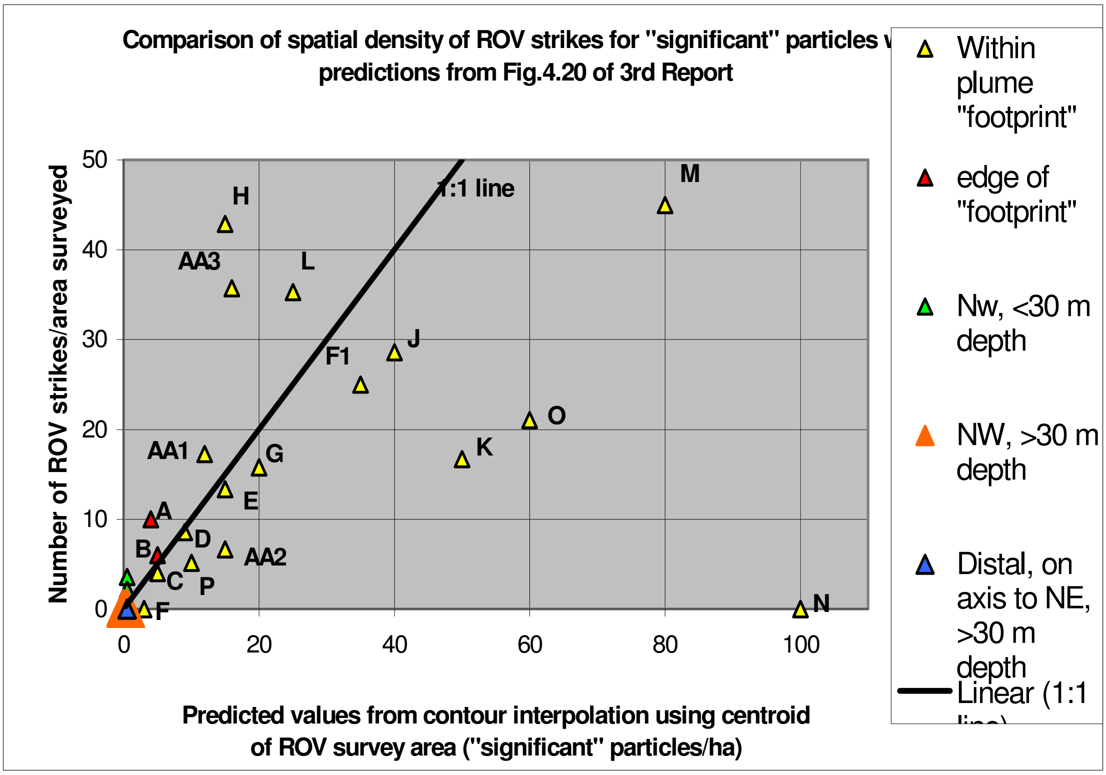

Fig. 5.13(a) Comparison of spatial density of ROV strikes for *significant* particles with predictions

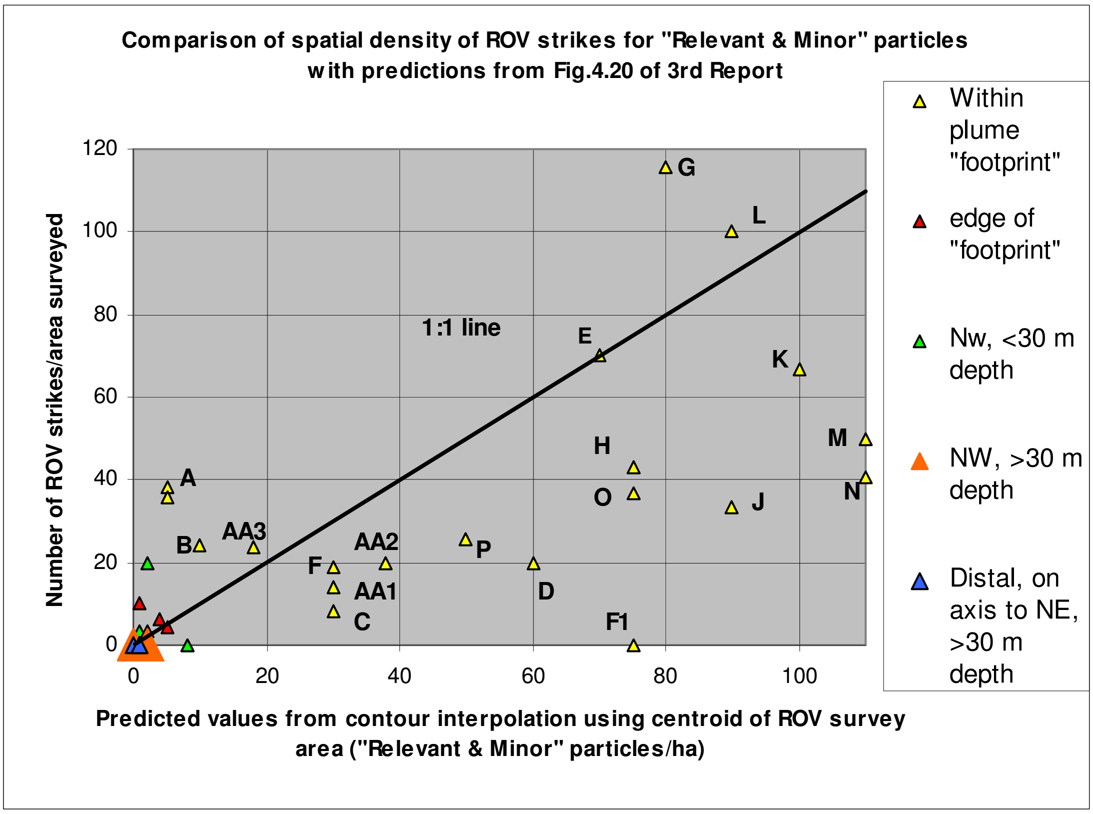

Fig. 5.13(b) **Comparison of spatial density of ROV strikes for *relevant & minor* particles with predictions**

5.4.4 A clearer pattern is apparent for *relevant* + *minor* particles in Fig. 5.13(b). Most of the areas lying within the central part of the mapped plume show lower ROV strike rates than predicted, plotting to the right and below the 1:1 line. This may be a reflection of the already noted tendency for ROV surveys to detect fewer particles with low activity and near the sediment surface.

5.4.5 Another method for comparing spatial densities is to assign both ROV strikes and diver finds to hectare squares and calculate the expected numbers per hectare from the proportions of every square surveyed by every method. This method differs from the previous comparison because many ROV areas lie within more than one adjacent hectare-square. Fig. 5.14(a) shows the result for *significant* particles, and Fig. 5.14(b) for *relevant* + *minor* categories. Both plots have widely scattered points, indicating discrepancies between the two surveys when data are aggregated in this way. The squares with large discrepancies of *significant* ROV strikes all lie near the centre of the mapped plume (I17, I18, J18, L20 on Fig. 5.14(b)), but this pattern is not consistent, as two other central squares (E16 & K16) show much larger densities of ROV strikes than predicted. As for the previous comparison, it appears that the distribution of *significant* particles that have survived removal by divers is more spatially variable than predicted by the contours in Fig. 5.5.

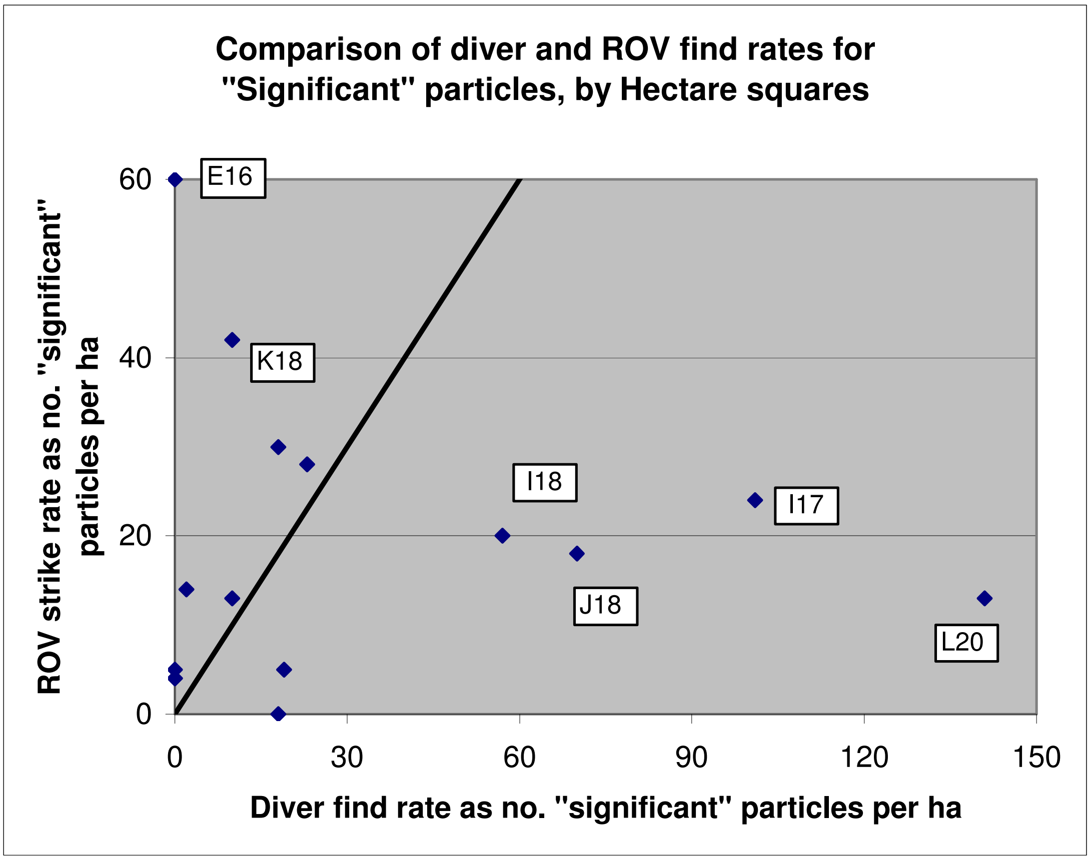

Fig. 5.14(a) Comparison of diver and ROV find rates for *significant* particles

5.4.6 For *relevant* + *minor* ROV strikes there is a complete contrast between comparison by survey area (Fig. 5.13(b)) and comparison by hectare-square, as shown in Fig. 5.14(b). Whereas comparison by survey area suggested that ROV surveys have found fewer *relevant* + *minor* particles than predicted from contours of the plume density, comparison by squares indicates the opposite. The most extreme discrepancy, in square I16, may be explained by the small proportion of the square surveyed (2.8%) and the exaggerating effect that this may have in extrapolation to the whole square. However, this explanation does not apply to three further squares that show a large discrepancy (K18, K19 & K20) where the proportions surveyed were 12, 36 and 19% respectively.

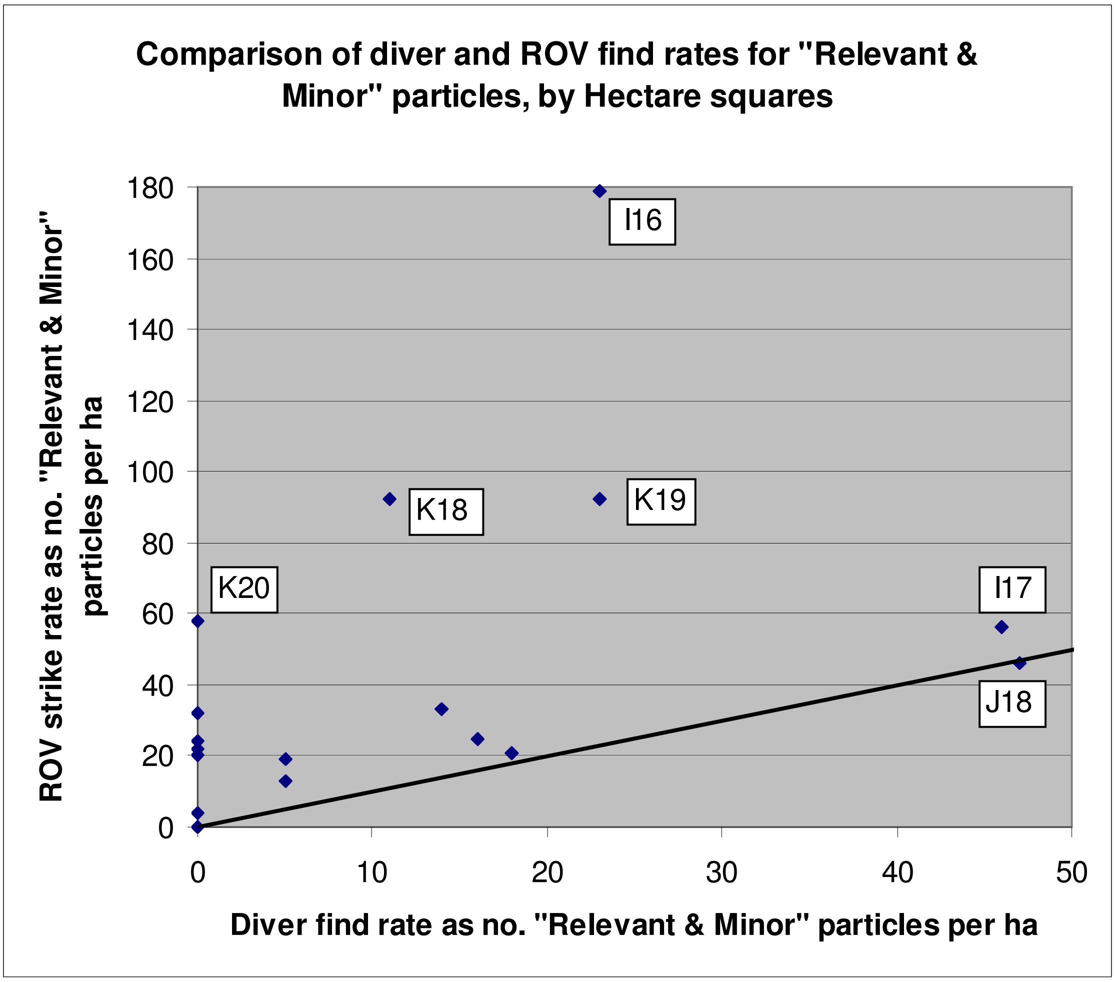

Fig. 5.14(b) **Comparison of diver and ROV find rates for *relevant & minor* particles**

5.4.7 Fig. 5.15 presents a third method of comparison, in which ROV strike rates are extrapolated to hectare squares and compared with contour values for the same squares. Thus, the two types of data have been derived on the same hectare-square basis from the original locations of strikes and finds, but the diver data have been smoothed and generalised by the contouring process. To assess the significance or otherwise of the scatter among the resulting data points, the uncertainties in the ROV strike rates have been calculated by the same method as used for diver finds in our Third Report (DPAG 2006), and expressed as error bars on Fig. 5.15. For the contour data, each square is plotted using the interpolated contour value for its mid-point, with bars displaying the range of contour values that intersect it. Separate plots are shown for *significant* (Fig. 5.15(a)) and *relevant* + *minor* categories of ROV strikes (Fig. 5.15(b)). In both plots the scatter of points is broadly symmetrical around the 1:1 line. This is an important result, as it suggests that the new ROV data has failed to reveal a systematic bias in the contour interpretation of the mapped plume, despite the complexities that are evident when comparisons are made on the basis of survey areas and/or individual squares for diver finds. The range bars and uncertainties used in Fig. 5.15 are also useful, as they allow the points to be classified on the basis of whether they lie within error of the 1:1 line, or significantly above or below it. These three cases are distinguished by blue, green and red colours on Fig. 5.15. Also shown are lines defining fixed ratios between spatial densities derived from ROV surveys and contour values, with a range from 4:1 to 1:4 for *significant* particles (Fig. 5.15(a)), and from 3:1 to 1:3 for *relevant* + *minor* (Fig. 5.15(b)). All the points lie within error of the outer lines in these ranges, a result which may be interpreted as indicating that predictions of particle density made for individual squares from the mapped plume of our Third Report (DPAG 2006) are unlikely to be in error by greater than a factor of four for *significant* particles, or by a factor of three for *relevant* + *minor*. Though these derived error factors are rather large, they apply only to estimates made for individual squares. Because the sampled squares have a roughly symmetrical distribution around the 1:1 line, errors will tend to cancel in any data manipulation that involves summation across large numbers of squares. This is important because the method used in our Third Report (DPAG 2006) to estimate particle numbers involved integration of the contour patterns for the mapped plume. This integration is effectively a summation, and the error in the integral will be reduced, compared with that for an individual square, by a factor roughly equal to the square root of the number of squares involved. As plume areas mapped in our Third Report (DPAG 2006) were 62 ha for *significant* particles and 113 ha for *relevant* + *minor*, these factors may be estimated from the square roots of these areas as roughly eight and 11 respectively. Thus, the additional data provided by ROV surveys implies that the uncertainty in our Third Report (DPAG 2006) estimates of particle numbers was about +/- 50% for *significant* particles and +/- 25% for *relevant* + *minor*. These estimates of uncertainty are roughly comparable with the 95% confidence interval of +/- 33% given on the basis of total particle counts in our Third Report (DPAG 2006).

5.4.8 The importance of this result is that the ROV surveys provide data which broadly confirmed the previous estimates of particle numbers. The symmetrical distribution of discrepancies between ROV and contour estimates of spatial densities suggests that the contouring methodology that was followed in our Third Report (DPAG 2006) is robust and does not lead to any detectable bias in the overall numbers of particles present.

Re-Evaluation of Total Particle Numbers

5.4.9 Our Third Report (DPAG 2006) estimated the total numbers of *significant* particles in the main plume as 1300 ± 33%. This was based on integration of the contoured pattern of spatial density of finds on the sea floor. The contour pattern used is reproduced in Fig. 5.5, along with the modifications that are required in the light of the new data from ROV surveys. The detailed comparisons between old and new data made in this section suggest that the methodology of our Third Report (DPAG 2006) was fairly robust in estimating overall particle numbers, and gave rise to uncertainties similar to those revealed through repetition by ROV of areas previously covered by diver surveys. In the light of this finding, it is legitimate to use a similar integration technique to produce a revised estimate for the total of *significant* particles present, incorporating the ROV data. Rather than re-integrate the entire contour pattern, the numbers of extra particles implied by the difference between old and new contour patterns has been determined. For *significant* particles, this amounts to 49 extra particles compared with the

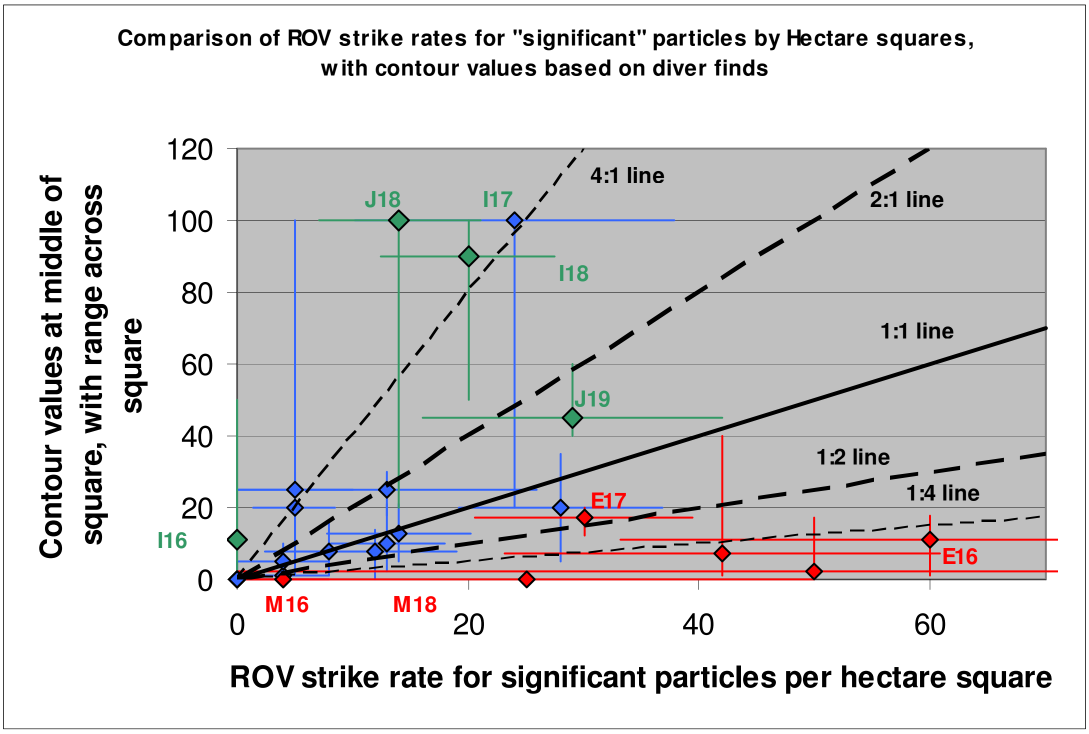

Fig. 5.15(a) Comparison of ROV strike rates for *significant* particles by hectare squares

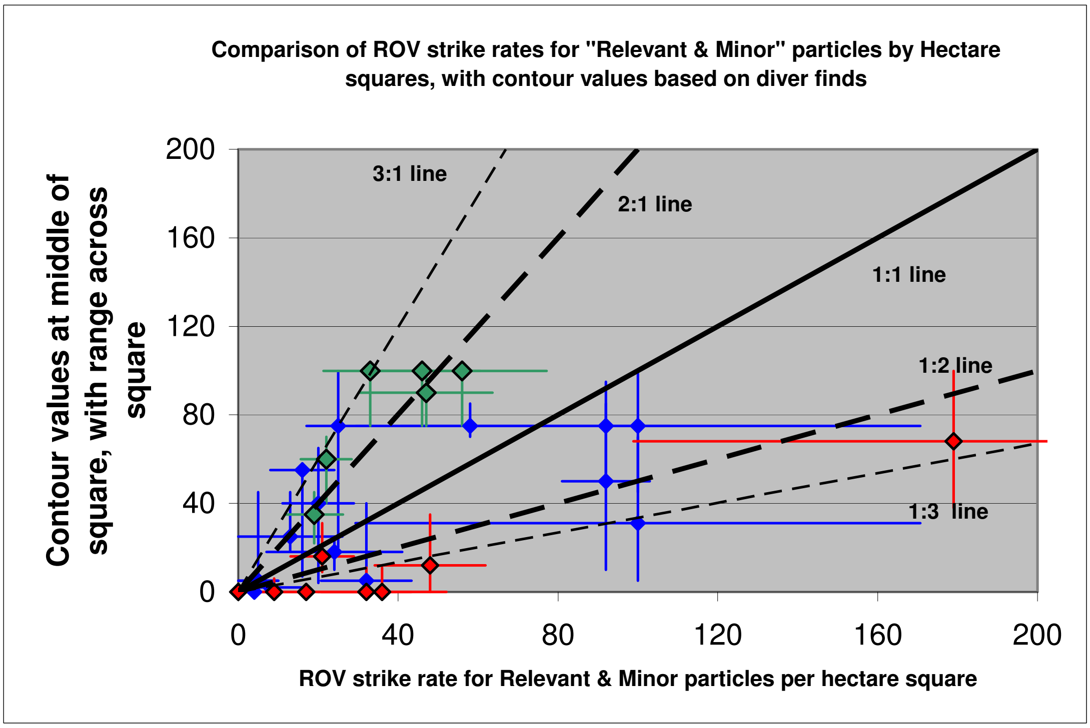

Fig. 5.15(b) Comparison of ROV strike rates for *relevant* & *minor* particles by hectare squares

value of 1300 in our Third Report (DPAG 2006). Thus the new ROV survey data has confirmed that our Third Report's (DPAG 2006) estimate of total *significant* particles was substantially correct, being less than 4% below a revised value of 1350 ± 33%.

5.4.10 Applying the same methodology to the contour patterns shown in Fig. 5.6 for *relevant* + *minor* particles leads to an estimate of 385 extra particles in the slightly wider plume indicated by the ROV data. This increase is less than 8% of our Third Report (DPAG 2006) value of 4900 particles with activities less than 10^6 Bq ^{137}Cs, again implying that the previous estimates for *relevant* and *minor* particles were broadly correct. Dividing the extra particles between *relevant* and *minor* is problematic, because the methodology used in our Third Report (DPAG 2006) cannot be followed. It is a reasonable assumption, however, that the proportions are much the same as in the main plume as a whole.

5.4.11 The revised estimates for numbers of particles are summarised in Table 5.1, including percentage changes compared with our Third Report (DPAG 2006). Table 5.2 provides similar information for the Western plume extending into Sandside Bay.

Table 5.1 Estimated Total Numbers of Radioactive Particles in the Main Plume Offshore from Dounreay

Particle class	Best estimate	Lower 95%ile	Upper 95%ile	Increase *cf* Third Report
Significant	1350	900	1800	4%
Relevant	1400	950	1900	8%
Minor	3800	2550	5070	8%

Table 5.2 Estimated Total Numbers of Radioactive Particles in the W Plume Extending into Sandside Bay

Particle class	Best estimate	Increase *cf* Third Report
Significant	None found	-
Relevant+Minor	400-500	600%

5.5 The Implications of the ROV Data

5.5.1 The first conclusion that should be drawn from the new ROV surveys is that they provide no evidence that would require major revision of our Third Report's (DPAG 2006) estimates of particle numbers in the main plume. The ROV surveys have shown that the seaward edge of the plume was previously mapped rather too near the shoreline, and the new contours in Figs 5.5 and 5.6 lie somewhat further to the NW than their previous equivalents. However, the overall shape of the plume remains the same, and the new estimates for total numbers of particles within the plume are only a few percent higher than the values in our Third Report (DPAG 2006).

5.5.2 The implication of this finding is that the ROV data are compatible with the conceptual model of particle dispersal, storage and transportation, given in our Third Report (DPAG 2006) and summarised here in section 5.2 and Fig. 5.2.

5.5.3 Beyond the main plume, the ROV surveys and beach finds made since February 2006 (the cut-off date for data in our Third Report (DPAG 2006)) confirm that *relevant* and *minor* particles are present to the E and W of Brims Ness, and that these form part of a thinly populated plume of such particles which extends as far as Murkle and Dunnet Beaches, 25 km along the coastline from Dounreay. This also supports the conceptual model described in our Third Report (DPAG 2006).

5.5.4 The finding of a single particle off Red Point proves that a few particles at least have been transported past the mouth of Sandside Bay and W along the coast. Such transport was predicted from the pattern of tidal and wave induced currents simulated in the Wallingford Model, so the Red Point find provides partial validation of this model. However, this model also predicts that spreads of particles should occur further W, and these have not so far been proved by the ROV surveys that have been made off Strathy Point (Fig. 5.11).

5.5.5 It is in the area of the W plume between the OD and Sandside Beach that the ROV data forces substantial revision of some findings in our Third Report (DPAG 2006). Apart from the single particle off Red Point, noted above, the area of sea bed covered by this plume remains much the same as envisaged in our Third Report (DPAG 2006), which was based on divers' finds. However, the ROV has revealed a much higher spatial density of particles on the sea bed within this 68 ha area, and consequently, a larger population within the plume, possibly as many as 400-500 *relevant* and *minor* particles combined. This estimate is a six-fold increase on the previous one in our Third Report (DPAG 2006). It is based on only 26 ROV strikes plus 16 diver finds, however, and it is possible that the true numbers are lower than the total that has been extrapolated from these known particles. If the assumptions behind our compensation for the effects of burial on particle detection are not correct, the true population could conceivably be as low as *c*. 250 particles. Nevertheless, this lower figure still represents a five-fold increase over the comparable value of 50 at the lower end of the estimated range in our Third Report (DPAG 2006).

5.5.6 Apart from the uncertainties of extrapolation from small numbers of finds in restricted survey areas, another possible reason for the discrepancy between present estimates and our Third Report (DPAG 2006) may lie in the systematic differences in activity and burial depths between the divers' finds and the ROV strikes in the W plume area. Figs 5.16(a) and 5.16(b) compare these. They clearly show that the ROV found a much higher proportion of particles buried below 100 mm depth than the diver surveys were able to do. The ROV strikes covered a range of activities that overlap with the divers' finds, but are, in general, higher by about one order of magnitude. These discrepancies mirror those already described above for the offshore populations taken as a whole, but are more marked, perhaps because of the generally low activities seen among all finds in the W plume, compared with the area around the OD where large numbers of *significant* particles occur.

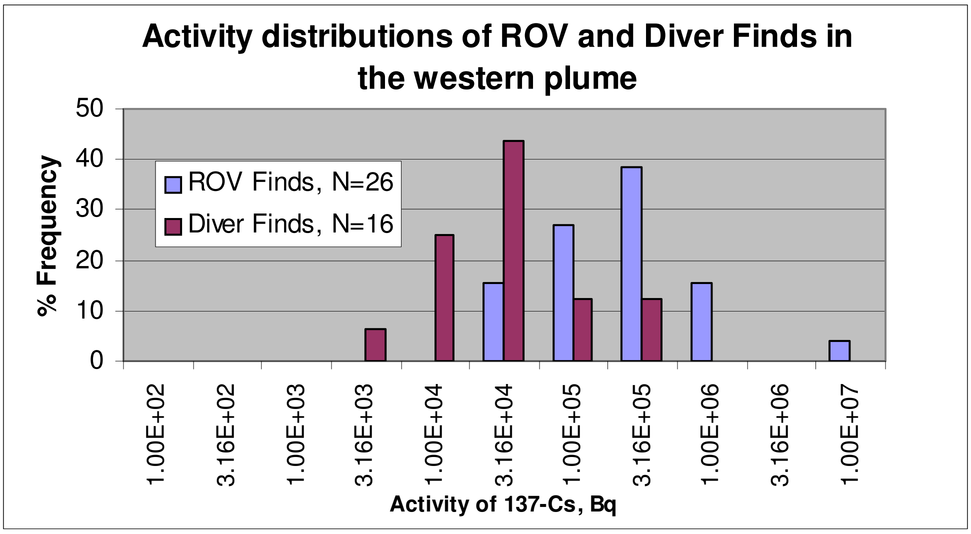

Fig. 5.16(a) Comparison of frequency distributions between ROV surveys and diver finds for particle activities

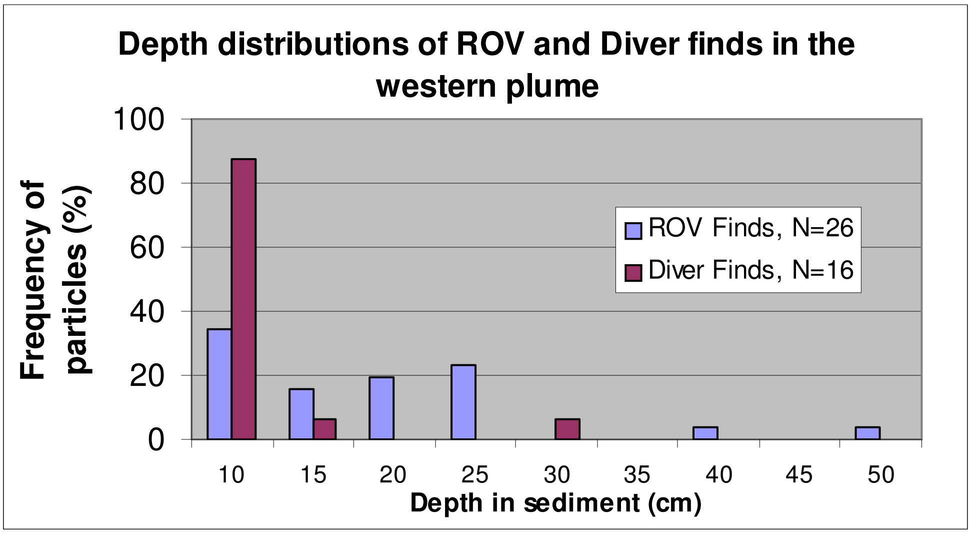

Fig. 5.16(b) Comparison of frequency distributions between ROV surveys and diver finds for depths of burial

Implications for Particle Transport to Sandside Beach

5.5.7 The larger population implied by the ROV surveys in the W plume has important implications when considered in conjunction with the conceptual model of overall particle migration outlined in 5.2 and Fig. 5.2. This conceptual model was developed in our Third Report (DPAG 2006) and has been substantially upheld by the new data from ROV surveys. It has been suggested that the offshore plume was in a near-steady state for over a decade prior to the onset of large-scale removals of particles from the sea bed in 2000-1, based on the lack of any significant long-term trend in the numbers of arrivals on the Dounreay Foreshore between 1984 and 1999. If this concept of a steady-state transport system is extended to the W plume, it can be used to make a rough estimate of the mean transit time of particles between the OD and Sandside Beach.

5.5.8 Across the mouth of Sandside Bay, the main W plume enters the Bay itself. However, *minor* particles that are, or have become, silt-sized would be transported away from the area and, as implied by the finding of a single particle in the area around Red Point, some may pass by the Bay. *Minor* particles are also detected less efficiently and reliably within both the sea-bed sediments and the beach.

5.5.9 DPAG has focused on *significant* and *relevant* particles because these are of particular interest in terms of public health. No *significant* particles have been detected so far, either in the W plume or on Sandside Beach, although this possibility cannot be excluded, as discussed in Chapter 6.

5.5.10 Especially in recent years, *relevant* particles have been detected reasonably efficiently down to 300 mm on the beach (Chapter 4). Once in the Bay, *relevant* particles can be washed onto the beach itself and, once there, be returned to the sea bed in the Bay or be removed *via* the programme of monitoring and retrieval. The residence time of a given particle within the beach itself would depend on the prevailing weather conditions. In general terms, however, some particles must return to the sea because large numbers have not been found when monitoring resumes after a long period of interruption. Chapter 6 of this report discusses this topic in more detail.

5.5.11 In a steady-state situation, the flux of *relevant* particles through the W plume should be equal to the rate of arrival of such particles on Sandside Beach. This arrival rate is difficult to estimate because monitoring has been irregular and the techniques adopted have changed. However, if it were assumed that, generally, most particles arriving at the beach returned to the sea soon afterwards, then the number of particles present in the beach at a given time would represent a crude estimate of the rate of transfer onshore. From Table 6.7 in Chapter 6, about two *relevant* particles are expected to be on Sandside Beach every month.

5.5.12 There is very considerable uncertainty in the estimates of the numbers of particles (both *relevant* and *minor*) in the W plume. Our Third Report (DPAG 2006) estimated that, of the offshore *relevant* and *minor* particles, about 30% would be *relevant*, while for those particles retrieved from the W plume the corresponding value was about 10%. On this basis, if the total number of particles in the W plume were 500 then the number that would be *relevant* would be in the range 50 –150. Taking these values with an arrival rate for *relevant* particles of about two per month would imply an average residence time of between about two and six years for *relevant* particles within the W plume.

5.5.13 An alternative approach to using *relevant* particles to estimate residence time in this way is to use all the particles in the W plume, *i.e.* both *relevant* and *minor* particles taken together. Once again, it is difficult to estimate the net arrival rate on Sandside Beach. If it is assumed that particles normally return to the Bay within a fairly short time after reaching the beach, as is implied by the lack of large build-up following interruptions of monitoring and removal, then the best estimate of the flux of particles through the W plume is the average rate of removal of particles from Sandside Beach. The available data permit two estimates to be made of this average rate, based on (a) the whole period of monitoring, and (b) on the shorter period in which Groundhog Evolution has been in operation. Case (a) involved 109 particles being recovered over 47 months of monitoring, an average removal rate of 2.3 particles per month. Case (b) involved 27 particles being removed over six months, an average of 4.5 particles per month. To estimate residence time, these two alternative removal rates must be combined with the population of *relevant* plus *minor* particles present in the W plume, which has been estimated as 400-500. Different combinations of figures provide estimates in the range 7 to18 years for the residence time of undifferentiated particles.

5.5.14 The residence time in the plume can be considered equivalent to the average time needed for a particle to travel from near to the OD onto the beach at Sandside. DPAG recognises that this approach is highly approximate with large areas of uncertainty, as indicated by the spread of estimates made using different approaches in the previous two paragraphs, from 2 to 18 years. Consequently, we conclude only that the average transit time to Sandside Beach is likely to be of the order of a decade.

5.6 The Possibility of Biological Caches of Particles in the Offshore Environment

5.6.1 The search for particles offshore has been mostly in areas of soft sediments, mainly sand or sandy-gravel mixtures. This is partly because, if the particles are behaving like sediment grains, such areas are the obvious places for them to be deposited, and partly because of the difficulties and dangers of surveying rocky surfaces and other non-sediment surfaces with the equipment available. If particles were being retained in other sub-littoral habitats, such as in rock crevices, amongst seaweed or in mussel beds, many might have gone undetected because of bias in the type of areas surveyed. This section considers the results of a baseline survey of the marine habitats offshore and considers the implications for particle trapping.

5.6.2 In 2004, UKAEA commissioned a Littoral and Sub-Littoral Baseline Report from SAMS Marine Research Services Ltd, as part of its Site-Wide Environmental Statement. The purpose of this report was to describe aspects of the marine environment that have significantly changed during the operation of the facilities at Dounreay. It should be borne in mind that the investigations in the report were not designed to provide a detailed species list. It should also be noted that benthic communities can undergo severe fluctuations in composition on various timescales, so a single survey might not present a full picture. Nevertheless the results do give some useful information on the biology of the offshore sediments.

5.6.3 Most of the samples taken during the survey came from habitat types classified as rippled fine sand but a few were from other habitat types that are also represented, namely “heterogeneous”; “slightly shelly sand”; “slightly gravely rippled sand”; and one “sandy gravel”. If the species found in the survey are compared with biotope descriptions in the Joint Nature Conservation Committee’s marine database (see www.jncc.gov.uk/marine/biotopes) the closest match is with biotopes whose sediment substrates are described as “infra-littoral medium-to-coarse and gravely sand subject to moderately strong water movement”. This is in line with expectations from our analyses of particle and sand migration in our

Third Report (DPAG 2006), as well as earlier in the present section, and it is also in line with the bottom-current velocities and sediment-transport conclusions from the Wallingford Model commissioned by UKAEA and briefly described in our Third Report (DPAG 2006).

5.6.4 Within the types of habitat present off Dounreay there are two main means by which particle trapping could be promoted biologically: through bioturbation of sediments leading to particle burial, or through sediment trapping in shell beds.

5.6.5 Many species of infauna that inhabit soft sediments feed by drawing water and suspended material down from the surface layers of sediment into their burrows. This activity results in bioturbation of the sediment. The process could cause particles to become buried, possibly to be returned to the surface at a later date. However, there is no indication from the species lists in the SAMS report that bioturbation of sediment is likely to occur to any great depth. Most of the infauna consists of species that are shallowly buried and which do not play a major role in the bioturbation of sediments. There are a few records of burrowing sea urchins but these are not present in sufficient numbers to produce a significant bioturbation effect. It may be concluded that biological factors do not play a major role in the vertical distribution of particles within the offshore sediments.

5.6.6 Shell beds are areas of sea floor that have been moderately or densely colonised by shelly creatures that are attached to the substrate, which may be sediment or rock. The species list in the SAMS report includes horse mussels (*Modiolus*). These occur on a range of substrates from muddy gravels through to hard rock. They are restricted in range to water depths of about 50 m. Where there are strong currents, stony and gravely substrates tend to accumulate between individual mussels in a colony so that a small biogenic reef forms. *Modiolus* beds are known to persist for decades or even hundreds of years. Sand grains, and possibly also radioactive particles, may become trapped in the byssus threads anchoring the mussels. DPAG has raised this possibility with UKAEA and has suggested that survey work be carried out to determine the possible presence and distribution of mussel beds in relation to the maximum extent of the particle plume as detailed in our Third Report (DPAG 2006).

5.6.7 Areas of heterogeneous sediments were identified in the SAMS report, but were not mapped in detail because their distribution was patchy. Rather a small set of species occurred in the single sample dredged from this habitat type, but the information given is insufficient to say whether this was because of genuine paucity of biota or because the sample contained relatively little of the soft sediment in which much of the fauna would have been living. However, some video footage exists showing areas of heterogeneous sediment colonised by a well-established epifauna, which suggests that these areas of sea bed may be disturbed to depth only rarely. Thus, if particles were to come to rest and be buried by the activities of sediment feeders in the pockets of fine, soft sediment between coarser blocks and gravel, they would probably remain *in situ* for a considerable time.

5.6.8 In response to our concerns, UKAEA has carried out a desktop study to investigate the prevalence of gravel, shingle and mussel beds in the vicinity of the OD (ref. UKAEA LRP(07)P032). The study found no evidence of mussel beds or heterogeneous sediment habitats within the main plume of particle contamination. It was concluded that:

- There are no known gravel beds in areas local to the OD or within the accepted particle plume area;
- Although potential biotopes have been identified near to the Dounreay site, from observations and records there does not appear to be a significant mussel population;
- Large populations of mussels do not occur associated with gravel beds.

5.6.9 Thus, it appears that while the possibility still exists of biological *caches* of trapped particles in heterogeneous gravel epifauna, and/or mussel beds, there is no evidence that it has been a factor in the main plume. DPAG has noted that there may be opportunities for divers to carry out further limited searches for mussel colonies during work around the OD in 2008, but regrets that no surveys have been planned for further afield. The areas beyond the mapped plume, towards Crosskirk and Brims Ness where particles have been found, may have coarser substrates with the possibility that mussel beds may be present which could have trapped further particles.

5.7 Conclusions

5.7.1 This Chapter has reviewed the new data that have become available since preparation of our Third Report (DPAG 2006) on the distribution and numbers of particles on the sea bed. The new data have mostly been acquired using a Remotely Operated Vehicle (ROV) for detection of particles, and an algorithm for estimation of their ^{137}Cs activity and burial depth within the sediment on the sea floor.

5.7.2 The new data suggest that the shape of the main particle plume illustrated in our Third Report (DPAG 2006) is substantially correct, but that minor modifications are required on its seaward, NW side. The 8 km extension of the plume along the coast to Brims Ness has been confirmed by the identification of further particles to the E of the headland there. Although no new particles have been found on the sea bed to the E of this, a single particle was located on Murkle Beach, a small beach within Dunnet Bay. This confirms that the plume extends at least 25 km E along the coast from Dounreay.

5.7.3 W from Dounreay, the new ROV data have confirmed that an area of 68 ha of sea bed contains a plume of particles that leads along the coast and into the mouth of Sandside Bay, ending at the beach there. It is this plume which is the immediate source of supply for the particles that are being found by monitoring on Sandside Beach. A single particle has been found on the sea bed off Red Point, W of the mouth of Sandside Bay. This find partially confirms the modelling study by HR Wallingford, described in our Third Report (DPAG 2006), which indicates that sand is transported W along this section of coastline. However, ROV surveys further W, near Strathy Point, have failed to locate any particles within a region in which the Wallingford Model suggested they should be present.

5.7.4 The new data have been used to revise our estimates of particle numbers that were present on the sea bed. The total numbers (*i.e.* the numbers still present, *plus* those that have been removed by divers) within the main plume have been revised upwards by a few percent, to 1350 *significant* particles, 1400 *relevant* and 3800 *minor*. Our Third Report (DPAG 2006) argued that the uncertainty for such figures was ±33%, and this estimate has been approximately confirmed by a rough comparison of new and old data.

5.7.5 The estimated number of particles in the W plume between the OD and Sandside Bay has also been revised. Here the new estimate is five or six times larger than the old, with 400-500 particles being the best estimate for the total within this 68 ha area of sea bed, although it is possible that the true number may be as low as *c.* 250.

5.7.6 Taken as a whole, these findings are all compatible with the conceptual model of particle dispersal by tidal and wave-induced currents developed in our Third Report (DPAG 2006). Particles are concentrated in the area of sea bed around the OD, and decrease in activity and in the spatial density with which they occur on the sea bed, in both NE and W directions from the core of the plume. The *c*. 40-year longevity of the plume is caused by two factors – particles are stored by burial in sediment, with occasional release during storms; and particles are fragmented from time to time, with the effect of maintaining the population of less active particles despite their relatively rapid rate of dispersion when not buried.

5.7.7 The new estimate of the number of particles present in the W plume has allowed deductions to be made regarding the average transit time for particles to progress from the area near the OD to Sandside Beach. Using different assumptions to interpret the available data, and also taking account of the uncertainties in the new estimate of particle numbers, a range of values from 2-to-18 years is obtained. We conclude from this large range that the transit time is in the order of a decade, but that the uncertainties are too large to be more specific.

5.7.8 Finally, there is little evidence of biological trapping of particles, although the possibility cannot be ruled out that *caches* may occur in areas of heterogeneous sediments colonised by epifauna, or in mussel beds. Though there are no significant examples within the main plume, the area towards Crosskirk and Brims Ness might contain biotopes that could act as potential traps. It would be worth making surveys of this area in future to establish this.

6. Arrival and Distribution of Particles on Public Beaches

6.1 Introduction

6.1.1 Our Third Report (DPAG 2006) reviewed particle finds on public beaches, with specific focus on Sandside Beach. Taking account of monitoring frequency, and beach coverage, our Third Report (DPAG 2006) provided estimates of the monthly abundance of particles on Sandside Beach, which were then used in an assessment of risk to beach users. In the light of recent finds on Sandside Beach, this Chapter re-examines the number of particle finds on the beaches of Caithness (section 6.2). Section 6.3 then interprets the trends in particles detected on Sandside whilst taking into consideration changes in monitoring effort, including: a) the area of beach surveyed (the footprint) and b) changes in detection equipment. These data are then used to evaluate any change in the rate of finds on Sandside Beach and to provide improved estimates of the numbers and abundance of *relevant* particles important for the risk assessment discussed in Chapter 7. The potential for Sandside to accumulate particles following extended periods when monitoring was not permitted is addressed in section 6.4. The probability of a particle found on Sandside beach being *significant* is subsequently discussed and given context in section 6.6, prior to the discussion of the likely health implications of an encounter with a *significant* particle in Chapter 7 and possible future monitoring requirements in Chapter 8.

6.2 Numbers of *minor*/*relevant*/*significant* particles on beaches

Chapter 6 provides an updated report on the finds on Sandside Beach up to and including March 2008, when consent for vehicular monitoring was withdrawn. There is also a brief review of finds on the Dounreay Foreshore. Very briefly, with regard to other public beaches, following the recommendations of our Third Report (DPAG 2006), UKAEA undertook surveys of additional public beaches close to Dunnet including Murkle where a *minor* (1.3×10^4 Bq) particle was detected in April 2007 and where other radioactive items (not fuel particles) have also been found.

The Dounreay Foreshore

6.2.1 The Dounreay Foreshore is effectively closed to the public. Routine bi-weekly strandline monitoring has been carried out on the Dounreay Foreshore since 1983. Beta/gamma monitoring was carried out by means of hand-held Geiger Muller tubes until June 2002. Since then, the surveys have been carried out using a hand-held single-detector system based on the Groundhog Mark 1 system, as well as beta surveys using a large-area beta detector. In October 2004, Groundhog Evolution was introduced. Since October 2004, the Dounreay Foreshore has generally been monitored fortnightly, the exception being during the four months of the tern nesting season. The entire Foreshore has not been monitored since 2002, the focus being primarily on the sandier West Foreshore as particles are associated with sandy deposits. The rocky East Foreshore has been monitored only when there was evidence of sand accumulation. All monitoring ceased each year for the four-month duration of the tern nesting season.

6.2.2 Up to March 2008, 255 particles have been found. No particles were detected from February 2005 until September 2006. Fig. 6.1 shows a plot of the log activity of finds over time.

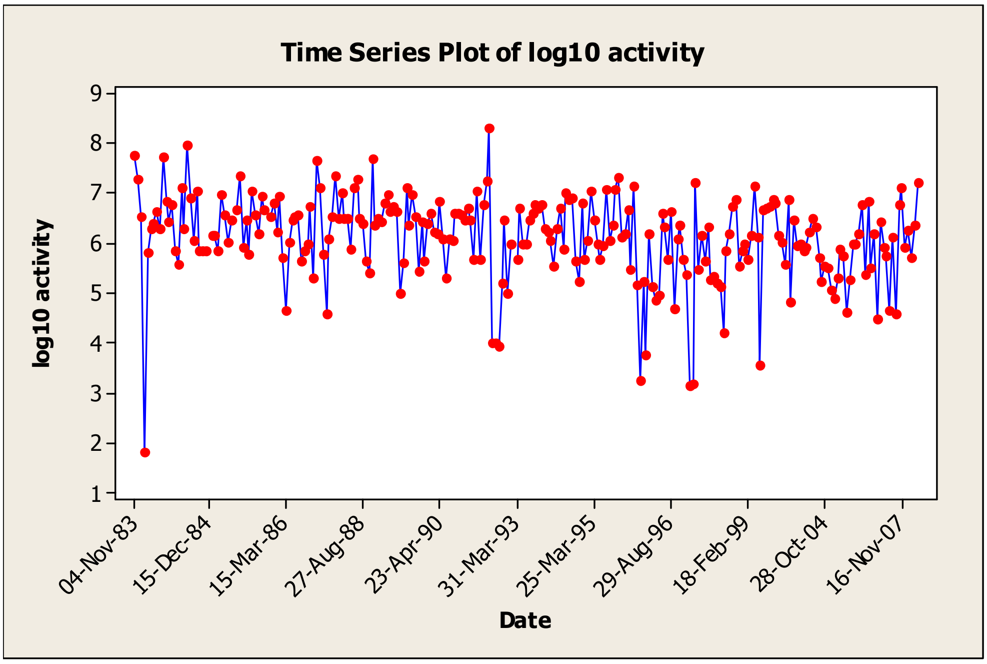

Fig. 6.1 **Log activity of particle finds on Dounreay Foreshore over time**

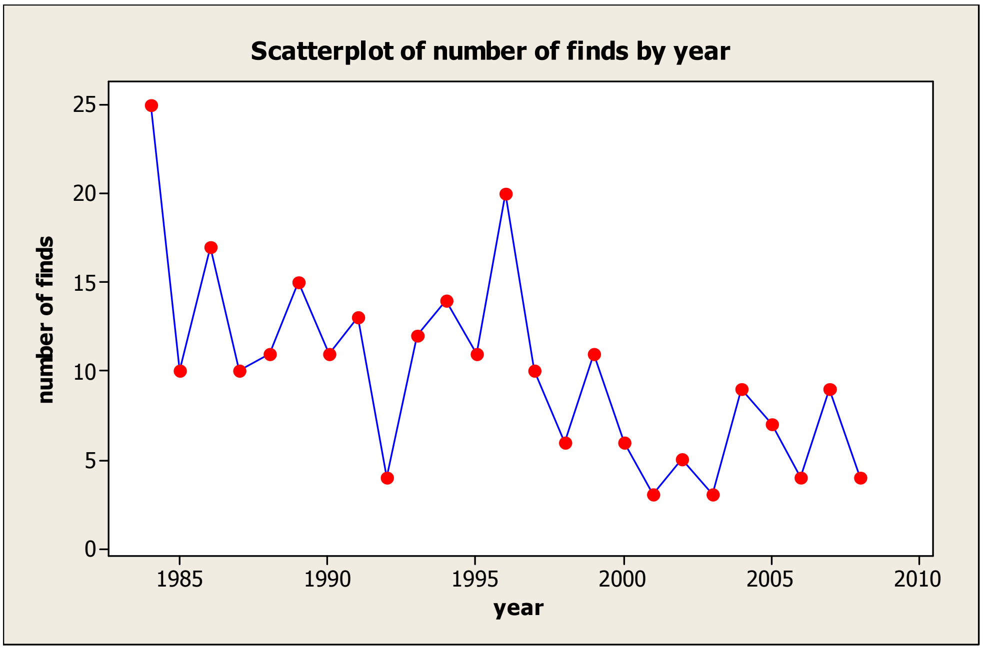

Fig. 6.2 **Time series plot of the annual number of particle finds on the Dounreay Foreshore**

6.2.3 Table 6.1 presents a summary of the particles finds (number of particles, arithmetic mean activity and mean depth) in each year since 1984 on Dounreay Foreshore. Up to March 2008, 255 particles had been found with a mean activity of 5.3x10^6 Bq ^{137}Cs.

Table 6.1 Annual Summary of Particle Finds on the Dounreay Foreshore since 1984

Year	Number of particles	Mean activity (x 10^6 Bq ^{137}Cs)	Mean depth found (mm)
1984	26	9.1	200
1985	10	4.9	100
1986	17	3.7	130
1987	10	9.3	120
1988	11	5.4	70
1989	15	7.7	80
1990	11	2.1	120
1991	13	2.0	160
1992	4	4.0	40
1993	13	2.7	126
1994	13	3.5	58
1995	11	5.5	115
1996	20	1.9	168
1997	10	2.1	90
1998	6	4.7	60
1999	11	3.3	166
2000	6	4.5	45
2001	3	2.7	23
2002	5	1.3	19
2003	3	2.4	67
2004	9	0.34	94
2005	7	1.4	86
2006	4	2.1	118
2007	9	2.8	67
2008 (to March)	4	5.4	93

6.2.4 The interpretation of the data in Table 6.1 and Fig. 6.2 is made more difficult by the lack of consistency in the area and frequency of monitoring. There is an apparent gradual decline in the numbers of particles being found, but no definitive statement can be made.

6.2.5 Fig. 6.1 suggests a gradual decrease in mean activity over the whole period, but there is an increase in the last two years (although based on small numbers of finds).

Sandside Beach

6.2.6 Until March 2008, 109 particles had been detected and removed from Sandside Beach. Fig. 6.3 shows a plot of $\log_{10}$ activity of particle finds, from the first find in 1984 until March 2008. The plot does not show a strong trend in particle activity but there is a suggestion of more variable-activity distribution of particles in 2007 and 2008. Fig. 6.3 suggests a very small gradual decline but also emphasises the increased variability in 2007 and 2008.

6.2.7 The dotplot (Fig. 6.4) below shows the activity of finds in every year from 1984 to 2008. Fig. 6.4, with 2007 and 2008 at the bottom, shows that the finds in 2007 have an extended activity range at both the lower and higher ends, probably reflecting the improved detector capabilities of Groundhog Evolution 2.

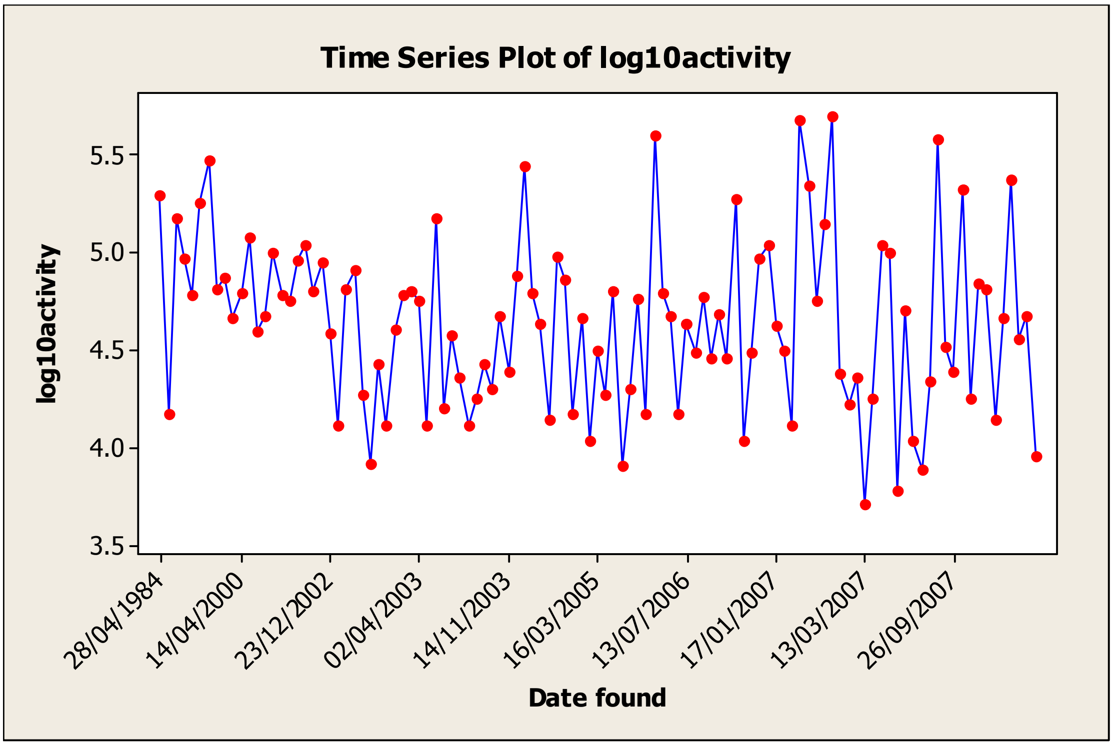

Fig. 6.3 Time series plot of particle activity at Sandside Beach

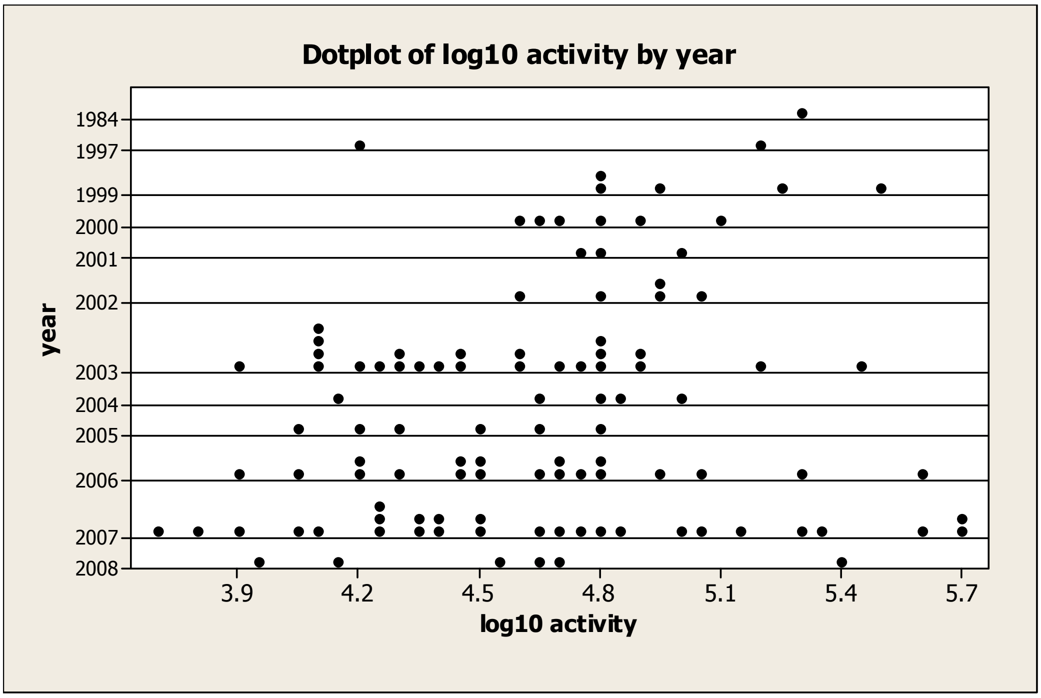

Fig. 6.4 Dotplot of log activity by year of find

6.2.8 Fig. 6.4 shows that the upper 25% of the activity distribution for 2007 (based only on six months monitoring) exceeds the maximum activities found in 2005, 2004, 2002 and 2001. Table 6.2 shows that the number of finds (27) in 2007 exceeds the largest previous figure of 24 in 2003.

Table 6.2 Descriptive Statistics: Log_{10} Activity by Year of Finds

Year	Number of particles	Mean log activity	Standard deviation	Minimum	Maximum
1984	1	5.30	*	5.30	5.30
1997	2	4.68	0.707	4.18	5.18
1999	5	5.06	0.299	4.79	5.48
2000	6	4.78	0.176	4.60	5.08
2001	3	4.85	0.133	4.76	5.00
2002	5	4.87	0.177	4.59	5.04
2003	24	4.52	0.377	3.92	5.45
2004	5	4.69	0.327	4.15	4.99
2005	6	4.41	0.297	4.04	4.81
2006	19	4.62	0.422	3.91	5.60
2007	27	4.64	0.563	3.72	5.70
2008[13]	6	4.57	0.495	3.96	5.38

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[13] To March 2008 only

6.2.9 Table 6.3 shows these finds broken down into *minor, relevant* and *significant* activities. It should be noted that no *significant* particles have been found on Sandside Beach.

Table 6.3 Numbers of Finds by Year and Activity Range

Activity	1984	1997	1999	2000	2000	2002	2003	2004	2005	2006	2007	2008	All
Minor,$<10^5$	0	1	3	5	2	4	22	5	6	16	19	5	88
Relevant, $>10^5 <10^6$	1	1	2	1	1	1	2	0	0	3	8	1	21
Significant, $>10^6$	0	0	0	0	0	0	0	0	0	0	0	0	0
All	1	2	5	6	3	5	24	5	6	19	27	6	109

6.2.10 Eight *relevant* particles were found in 2007, exceeding the previous maximum number by more than a factor of two (in 2006). Of the finds in 2007, 29% exceed 10^5 Bq; this is roughly twice that recorded in 2006. Earlier years yielded many fewer finds, and, hence, the percentage (and uncertainty on the figure) is large. However, these figures do need to be treated cautiously since standardisation for sampling effort may change the interpretation; this is discussed further in section 6.3. Moreover, Groundhog Evolution 2 (used for 2007 and 2008 monitoring) has an increased capability of detection of particles at depth, so the increased number in the *relevant* category may, at least in part, be due to the improved particle detection capability. This is also discussed further in section 6.3.

6.2.11 A possible seasonal pattern in finds, *i.e.* whether there are specific times of the year where the number of finds is greatest, could perhaps be related to storminess or to changes in beach height. This is explored below.

6.2.12 A consequence of the time gaps in the monitoring of Sandside Beach is the uncertainty in relating the incidence of particle finds to the time of year and hence to seasonal weather conditions. Table 6.4, column 5, shows the number of times since 1999 when survey has been permitted during particular months. Thus, survey results based on the 1999 – 2007 period are lacking in respect of nine of the months; as a result there are considerably less data that might have been relevant to seasonal influences had monthly survey been possible for the whole period (1999 – 2007). Against the background of the uncertainties posed by these limitations, and using only the figures available, it is possible to create a standardised rate of finds per survey for each month (by dividing the number of finds for that month by the number of times a survey was completed in that month).

6.2.13 The table below shows a pattern of higher numbers of total finds in February, March, April and in November (16, 26, 10 and 11 respectively from the total of 109) and a mean rate (per survey) higher in January, March, April, June and October.

Table 6.4 Summary of Finds by Month of the Year

Month	Number found	Mean activity Log_{10}	Activity Log_{10} St. Dev.	Number of times month surveyed from nine possible surveys	Mean rate of finds
Jan	7	4.83	0.525	2	3.5
Feb	16	4.58	0.478	7	2.3
Mar	26	4.50	0.440	6	4.3
Apr	10	4.69	0.388	4	2.5
May	3	4.18	0.071	2	1.5
Jun	5	4.82	0.508	2	2.5
Jul	9	4.64	0.296	4	2.25
Aug	5	4.42	0.338	4	1.25
Sep	7	4.90	0.536	4	1.75
Oct	6	4.73	0.366	2	3
Nov	11	4.78	0.422	6	1.8
Dec	4	4.85	0.200	3	1.8

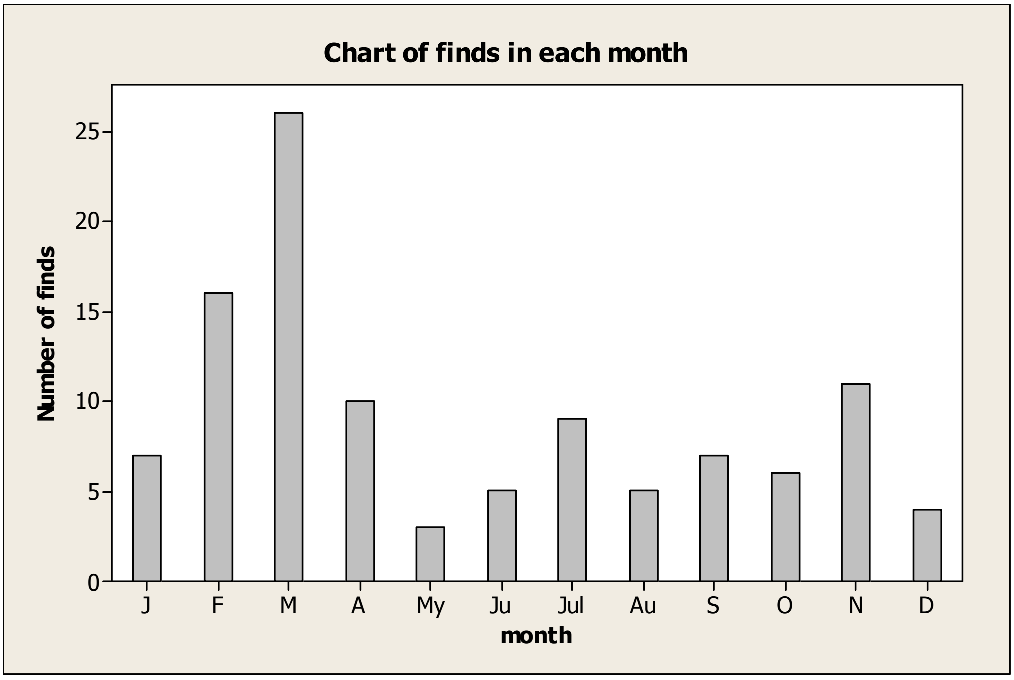

Fig. 6.5 Number of finds in every month from 1999

6.2.14 Fig. 6.5 shows the number of finds in every month over the period 1999-2007. There appears to be a suggestion that there is an increased number of finds in the early parts of the year, suggesting some seasonality that may be related to beach dynamics and storminess. Fig. 6.6 showing the standardised rates still suggests that there is a greater rate of particle finds in the early part of the year.

6.2.15 Formally, there is evidence to reject the hypothesis that the rates are equal in each month, with too many finds in January and March and too few in August – providing evidence for non-uniformity of particle finds over the year.

6.2.16 There is no evidence that the mean activity of finds varies over the year.

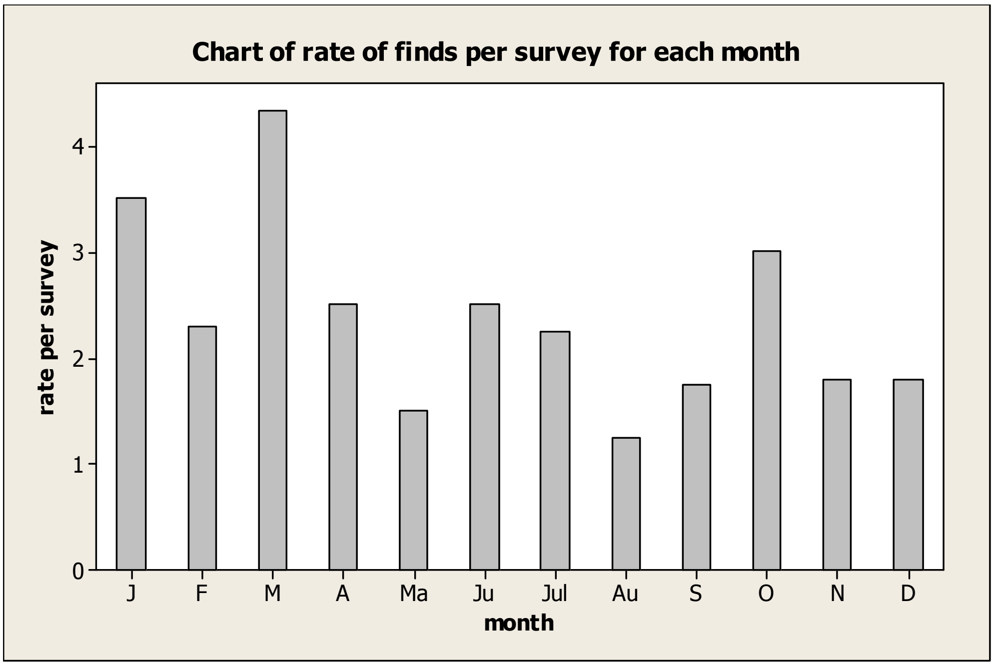

Fig. 6.6 Chart of the mean rate of finds in a month standardised for the number of times a month has been surveyed

Depth of Particle Detection

6.2.17 Distribution of depth of finds by year is shown in Figs 6.7, and 6.8. These show that the mean depth of finds has gradually increased, and for 2007 finds at least, there is a greater range of depth of finds, with three finds at greater than 200 mm depth. This reflects the greater detection capability of Groundhog Evolution 2, but should also be read against the background of incomplete results imposed by the periods when no data could be gathered.

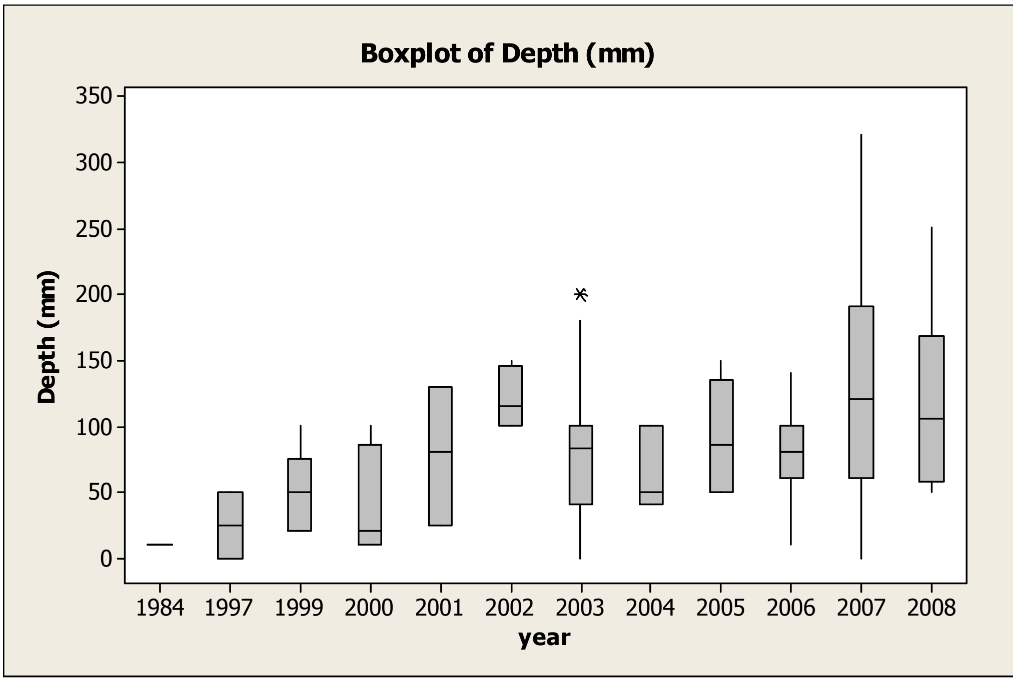

Fig. 6.7 Boxplot of depths of finds

Note: The boxplot is constructed to identify the median (central line), lower and upper quartiles (upper and lower lines of the box) and the range of the distribution of activities. * Represents an extreme value, identified as one which lies more 1.5x the height of the central box from the median.

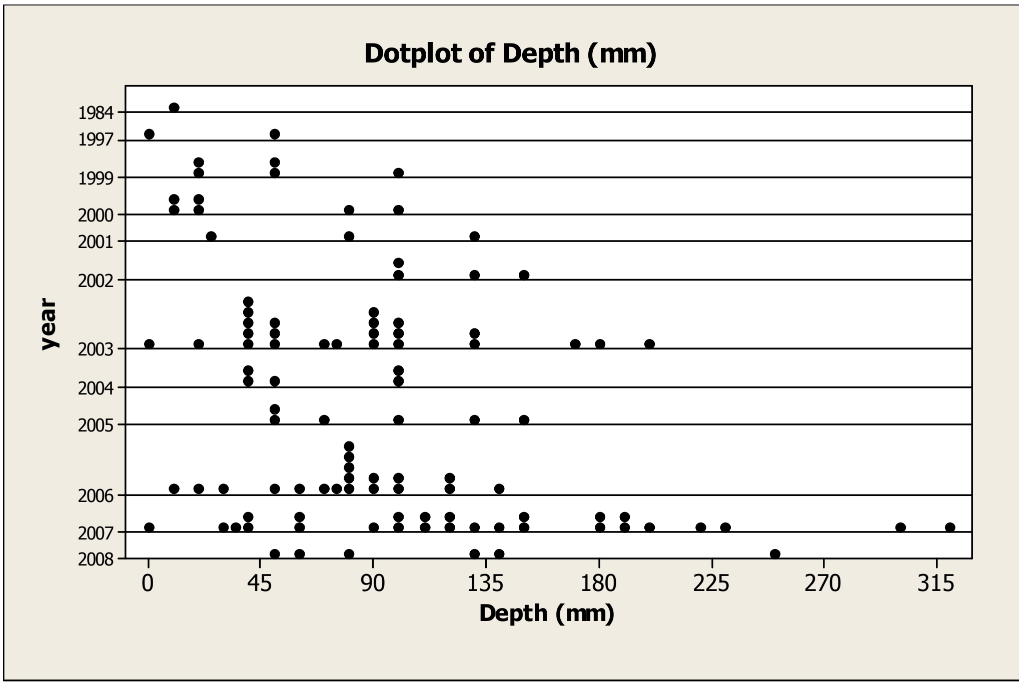

Fig. 6.8 Dotplot of depth of finds

6.2.18 Fig. 6.9 shows a scatterplot of activity ($\log_{10}$) by depth, coloured for every year. It shows, at the right hand side, that higher activity particles have been found at greater depth in 2007 and 2008. However, there is no suggestion that the upper range of activity has been extended beyond that previously seen. Later in the Chapter we will explore the effect of detection, probability on particle finds in 2007, and how this compares with earlier years.

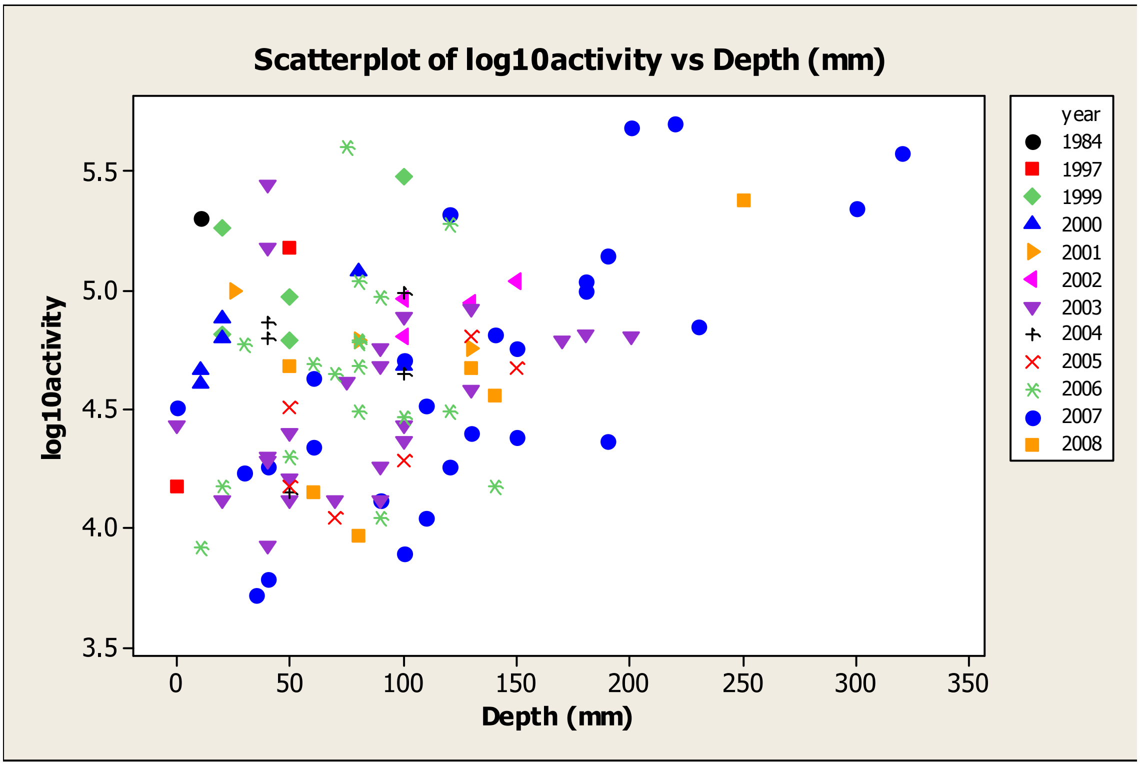

Fig. 6.9 **Scatterplot of log activity by depth**

6.3 Changes in Beach Particle Abundances in Sandside

6.3.1 Table 6.5 is reproduced from our Third Report (DPAG 2006) and provides the mean monthly abundance estimates for particles on Sandside according to the different versions of Groundhog monitoring systems. The table has been extended to incorporate the Groundhog Evolution 2 finds in 2007. It is notable that there is an apparent increase in the abundance of *relevant* particles found on Sandside Beach. There is no suggestion from the limited monitoring undertaken in March 2008 to contradict the 2007 estimated monthly abundances.

Table 6.5 Summary of Mean Monthly Particle Rates (ND = Not Detected)

Particle category	**^{137}Cs Activity**	**Groundhog Mark 1, 1999-2002**	**Groundhog Evolution 2002-2006**	**Groundhog Evolution II 2007 (March 2008)**
Minor	<10^4 Bq	ND	0.12	0.50 (1)
	10^4 – 4x10^4 Bq	ND	1.88	1.67 (1)
	4x10^4 – 10^5 Bq	0.77	1.06	0.83 (2)
Relevant	>10^5 Bq	0.23	0.12	1.17 (1)
All	Total	1.0	3.18	4.17 (5)

6.3.2 Plotting the mean monthly rate of particles detected on Sandside Beach, Fig. 6.10 clearly shows that there has been an apparent increase in the number of particles detected per month.

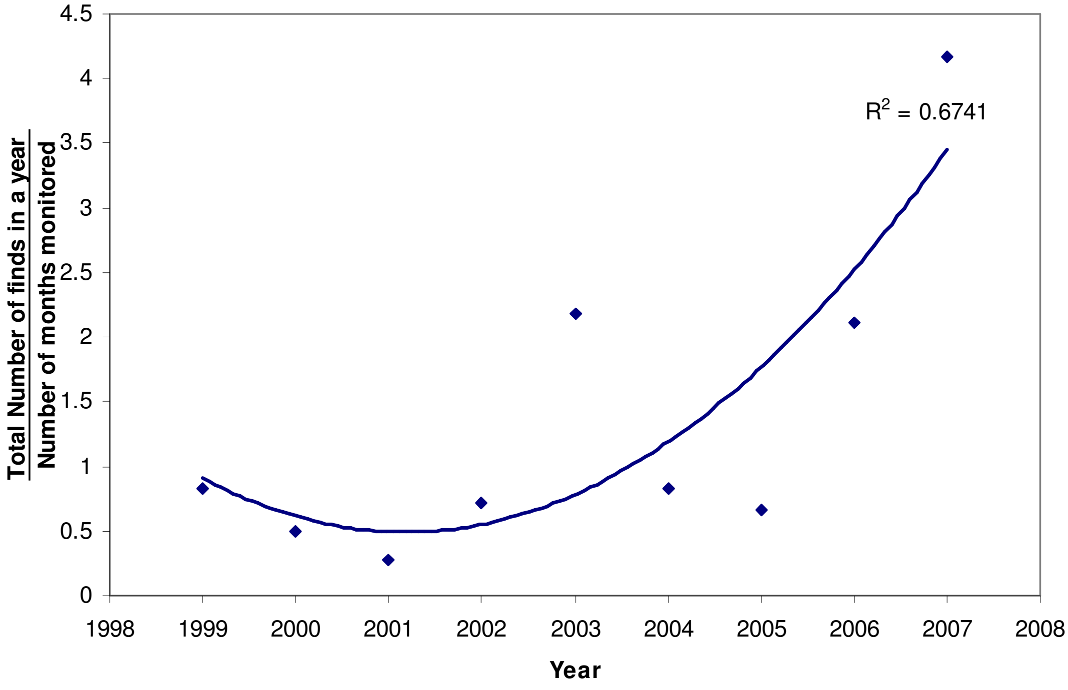

Fig. 6.10 Mean monthly rate of finds in each year for Sandside Beach

6.3.3 As discussed in 6.2, the raw data may be biased by the months in which monitoring was permitted on the beach and, as demonstrated in Chapter 4, the improvement in detection capability represented by the Groundhog Evolution and Groundhog Evolution 2 systems. These offer potential explanations for the apparent change in particle detection rates. The question, therefore, remains as to whether there have been any changes in number of particles on Sandside Beach. To answer this question, the data need to be corrected for the monitoring effort (beach area covered) and monitoring capability (detection efficiency). Integrated within this is also the potential influence of the seasonality of particle arrival or re-surfacing due to beach erosion which may also coincide with permission to access the beach.

Adjusting for Beach Footprint

6.3.4 Supplementary interpretation of the Sandside Beach finds follows from consideration of (i) the footprint of the survey (the area of the beach covered or sampled) and (ii) the total area surveyed, corrected for areas monitored more than once. The maximum exposed area of Sandside Beach calculated by UKAEA (pers. comm. 2006) is shown on Fig. 6.11[14] as 318,652 m^2. This is assumed to be the maximum area accessible by the public, depending on tide and beach elevation. Indeed, in the original TID, the area of 250,000 m^2 is stated as the minimum area to be monitored.

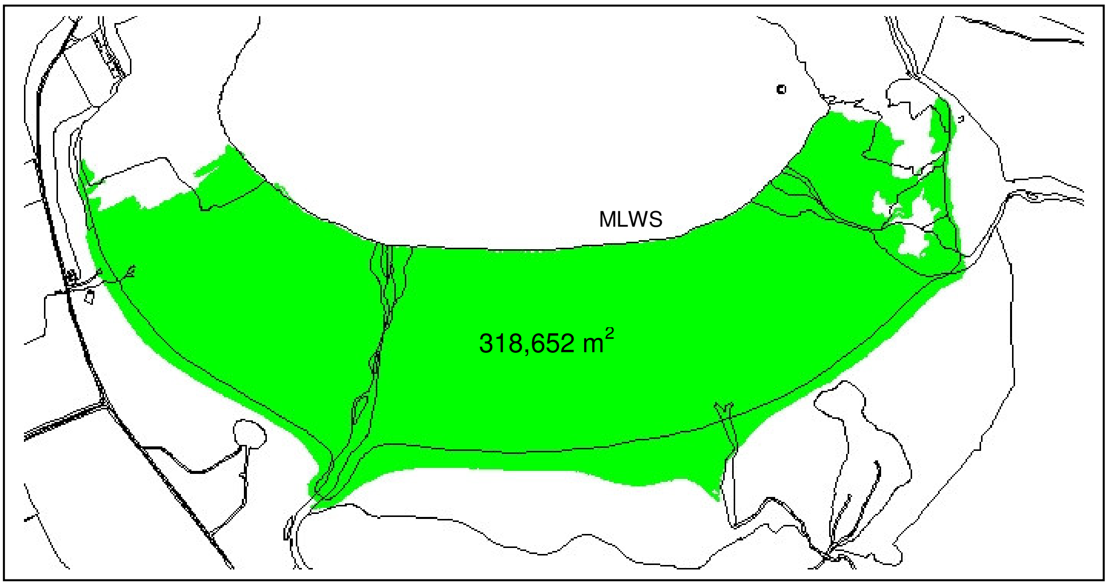

Fig. 6.11 The maximum beach area, estimated to be 318,652 m^2 (excluding the harbour area)

6.3.5 There is a considerable difference between the results of the total monthly area monitored (a function of measurement density) and the footprint of the area monitored. Fig. 6.12 demonstrates the reason for these differences. The optimal measurement density is 2.5 measurements per m^2. However, as the vehicle slows down, overlaps with previous runs, or stops to check the presence of a particle, the measurement density increases and thus the effective area monitored also increases. For example, for a stationary vehicle, the measurement density builds by 2.5 for every second the vehicle is stationary, *e.g.* a measurement density of 250 can be explained by the vehicle remaining stationary for 100 seconds. Fig. 6.12 therefore confirms that the footprint area is the correct parameter to be used in calculations using beach area.

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[14] There is a further area within Sandside Bay which is accessible-Sandside Harbour. However, no particles have been found at this location to date.

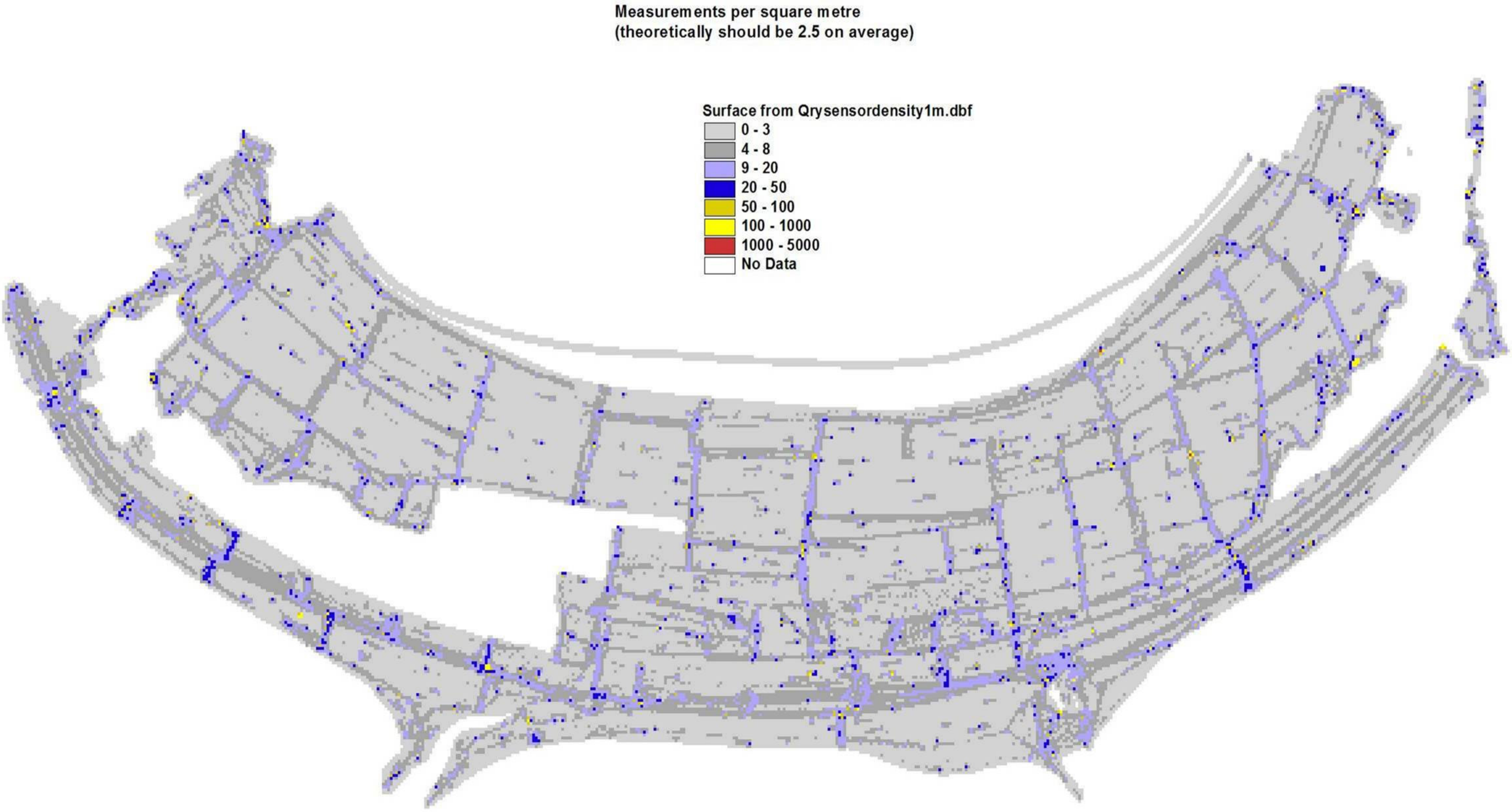

Fig. 6.12 The footprint and the amount of monitoring overlap contributing to the total areas reported (Cartwright and Gerrard, pers. comm. 2007).

6.3.6 To provide a spatial perspective of this coverage, Fig. 6.13 shows the frequency with which different parts of Sandside Beach has been monitored. The lower intertidal portions of Sandside have been less frequently surveyed.

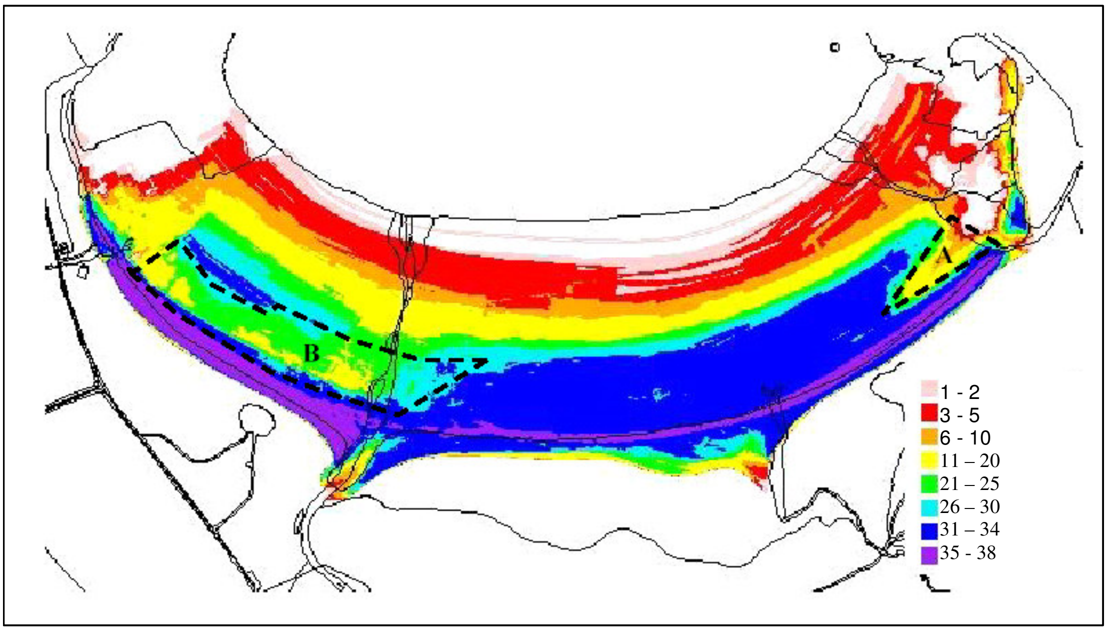

Fig. 6.13 Map of Coverage Frequency on Sandside Beach of a Total of 38 Surveys (Scirea *et al.* 2007)

6.3.7 Fig. 6.14 shows the calculated footprint through time. The results show that there was much variation in the monitoring footprint when Groundhog Mark 1 was deployed (until November 2002). More recently, efforts are being made to monitor as much as possible of the beach as practically accessible down to low water, resulting in footprint areas approaching but never exceeding 250,000 m^2 for Groundhog Evolution and Groundhog Evolution 2 surveys.

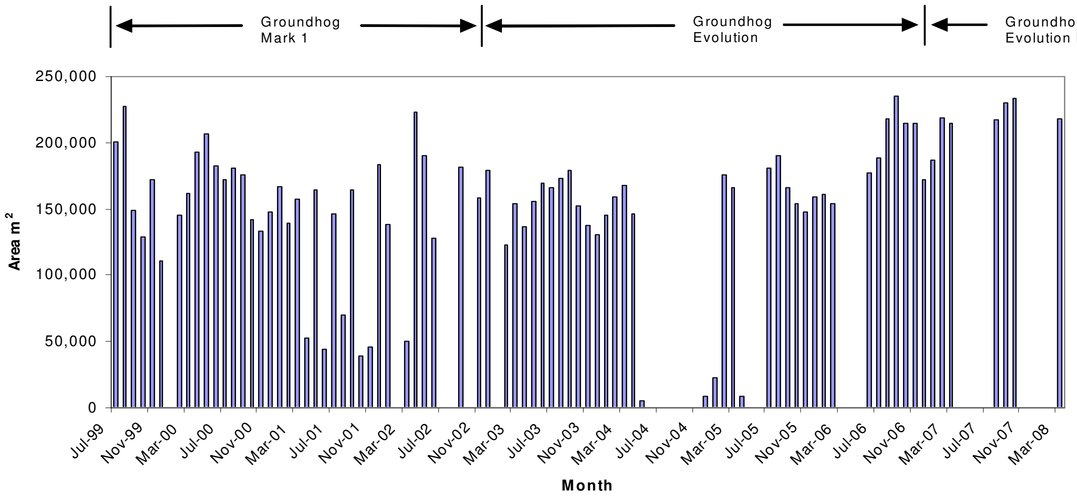

Fig. 6.14 The monitoring footprint with time and the times when vehicular monitoring access was not allowed

6.3.8 Fig. 6.15 illustrates the additional finds made within the lower intertidal reaches of Sandside Beach. It is interesting to note that UKAEA report that five (42%) of the 12 particles recovered from this portion of the beach over six months of monitoring were classed as *relevant* (Mackay, *et al* 2008), which is a greater proportion than found higher on the beach since particle monitoring began.

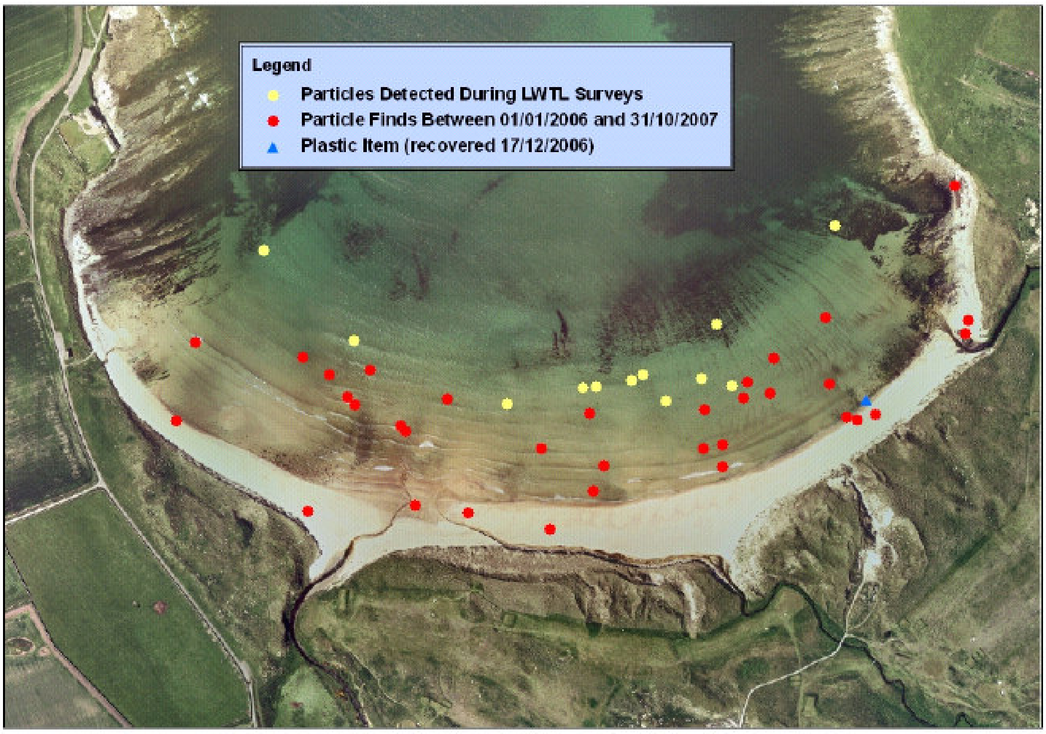

Fig. 6.15 Aerial view of Sandside Beach with particle finds (LWTL = Low Water Tide Line)

6.3.9 There is therefore a need to correct for monitoring effort, as measured by monitoring footprint when comparing particle find characteristics with time. A simple adjustment for the area surveyed is to imagine that the total number of particles on the maximum area of the beach that might be exposed at Mean Low Water Spring tide (318,652 m^2) is calculated by scaling up the number of particles found within the footprint by the ratio of the maximum area of the beach to the footprint area. This assumes the area sampled (effectively greater than 50% of the whole beach area, in most cases, as can be seen in Figure 6.14) is a representative sample of the whole beach during the period monitored. Thus the actual finds can be adjusted to account for the area of beach monitored and we can then convert the data to consider the 'potential' rather than actual numbers of particles that would have been detected on the beach.

Changes in the Number of Particles Detected per Month

6.3.10 The data shown in Figure 6.16 have been corrected for beach area monitored and normalised to 318,652 m^2. It is therefore equivalent to Fig 6.6 but now adjusted for the area monitored. The results show a non-uniformity in particle finds, with the late winter and early spring months yielding the greatest number of particle finds. This seems to coincide with the period when the beach rebuilds itself by sand accumulation following beach erosion during storms.

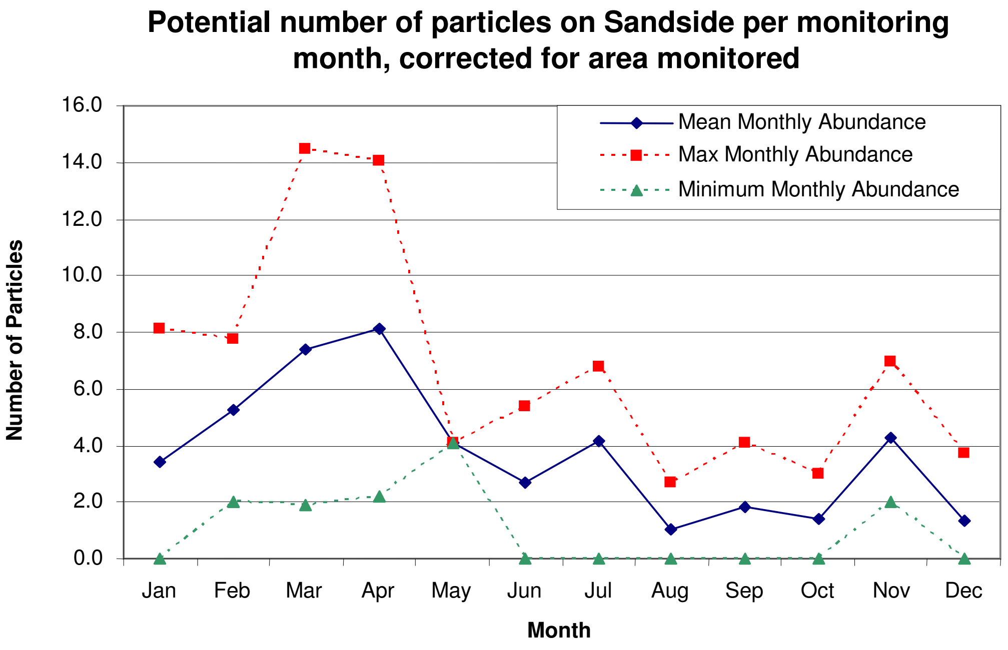

Fig. 6.16 **The change in the potential number of particles that may occur on Sandside for each month. Based on data collected between 2002 and 2007 (October)**

Adjustments for the changes in Equipment and hence in Particle Detection Probabilities

6.3.11 To examine any changes in the number of particles detected over time, we have to compensate for changes in detection limit. Retrospective prediction of notional particle finds by Groundhog Evolution or Groundhog Evolution 2 prior to November 2002 is not possible. However, an assessment of how many of the particles detected by Groundhog Evolution and Groundhog Evolution 2 could have been detected by Groundhog Mark 1 is possible and may enable us to assess whether there has been any intra-annual change in particle arrivals, at least for the more active *minor* particles and the *relevant* particles. This would provide some insight as to whether the apparent increase in finds since 2002 can be explained by the improved detection capability.

6.3.12 Our Third Report (DPAG 2006) described the empirical model for Groundhog Mark 1 detection, which was developed for the SEPA beach monitoring software. The results from the software compare favourably with the Beach Trials and UKAEA Sandpit trials. This software was used with Groundhog Mark 1 data from June 2002, with a mean operating velocity of around 0.8 ms^{-1}, to assess the probability of Groundhog Mark 1 detecting every particle recovered by Groundhog Evolution and Groundhog Evolution 2.

6.3.13 By calculating the probability of detection by Groundhog Mark 1 for every particle and systematically including only those particles with a Groundhog Mark 1 probability of detection of >0.2, >0.4 and >0.6, we can establish the possible time-series trends in particle detection.

6.3.14 Fig. 6.17 shows the trends by progressively including only those particles with an increasing probability of detection by Groundhog Mark 1. Whilst the data remain noisy, when only those particles with a probability >0.4 or >0.6 of being detected by Groundhog Mark 1 are added to the Groundhog Mark 1 data, the evidence for an increasing rate of particle arrivals with time is lost.

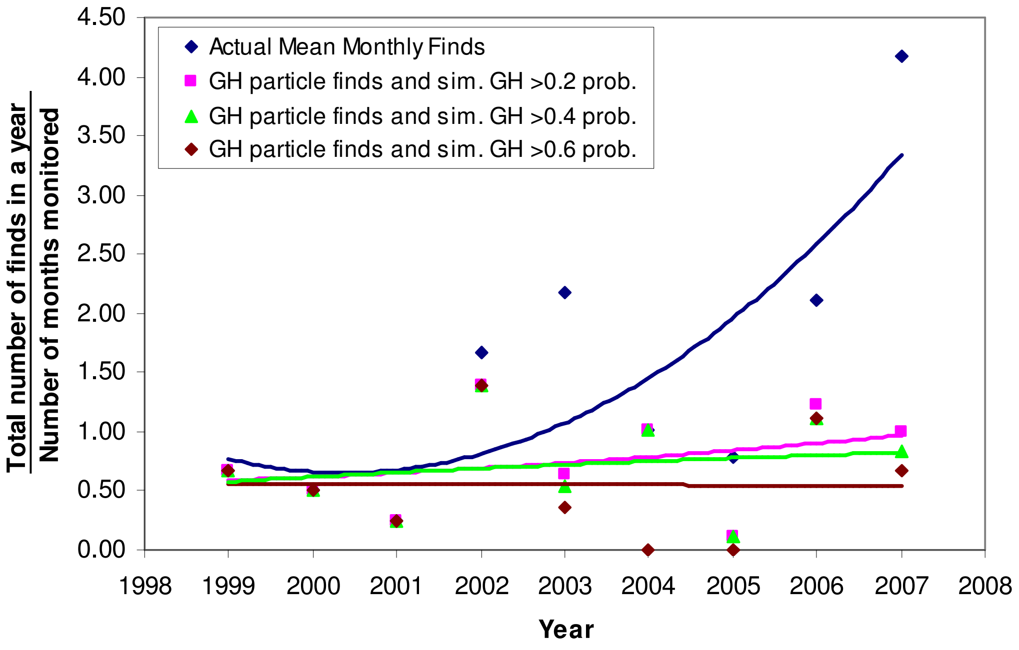

Fig. 6.17 Actual and predicted rates of particle finds on Sandside Beach

6.3.15 The predictions are made under the assumption that Groundhog Mark 1 had continued monitoring the beach under three different particle detection probabilities. Fig. 6.17 thus shows that the apparent increase in finds when corrected for sampling effort (number of months) and when adjusted for detectability, can be explained to a very large extent by the improved capabilities of the newer systems.

6.3.16 By additionally compensating for the variation in the footprint area monitored, and assuming that the area monitored is representative of the entire beach especially when averaged over a 12 month period, Fig. 6.18 provides little support for the hypothesis that the abundance of particles has increased. The data show considerable inter-annual variability so that trend estimation must be treated with caution.

6.4 Propensity to Accumulate Particles on Sandside Between Extended Periods of No Monitoring

6.4.1 Our Third Report (DPAG 2006) presented the preliminary results of beach-height monitoring, following the installation of high-accuracy kinematic DGPS instruments on-board the Groundhog vehicles. Since the preliminary work undertaken towards the end of 2005, UKAEA has been able to build a temporal database of beach height for approximately each 1 m^2 of beach monitored with an accuracy of ± 50 mm. A preliminary study by UKAEA (Scirea *et al*. 2007) of eight particles which were coincident at locations with unbroken time series (between September 2005 and December 2006) of beach height and beach profile information enabled an analysis of the recent provenance of every particle find. The results of the study have shown that particles can begin to be identified as being a new arrival to the site detected, *i.e.* washed in from a recent tide (between monitoring visits); *or* relocated by sediment translocation processes across the beach *or* a historical particle that has remained within the sediment profile.

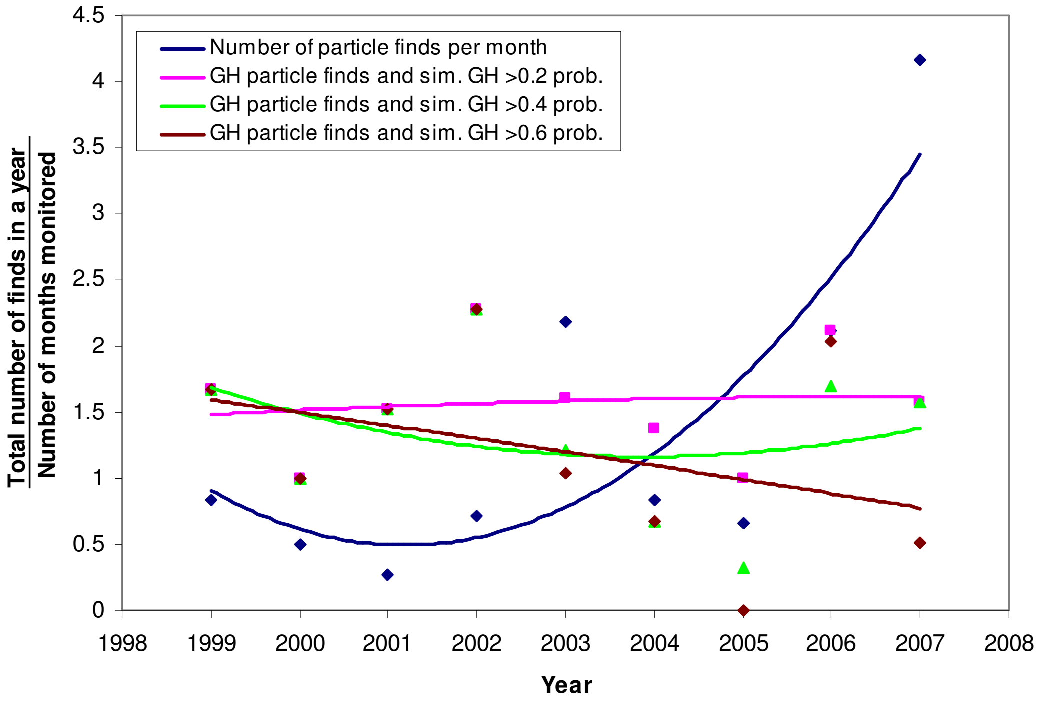

Fig. 6.18 Actual and predicted rates of particle finds on Sandside Beach corrected for beach area

6.4.2 For example, Fig. 6.19 (Pearson *et al.* 2007, p17) shows how a 4.9x10^{4} Bq ^{137}Cs particle was probably uncovered during a period of beach erosion since the previous survey in September 2006, and was detected at 60 mm in October 2006. The particle had not been detected in the previous four months of monitoring because it had been buried to a depth of at least 190 mm. In contrast, Fig. 6.20 shows the recent arrival of a 9.3x10^{4} Bq ^{137}Cs particle in December 2006, detected at 90 mm depth. The beach was at a lower level in the previous six months and thus must be a recent arrival at that location. Examination of the beach profile for this particle indicates that the upper reaches of the beach were being actively eroded and thus there is a possibility that the particle arrived from upper part of the beach rather than as a fresh deposit from the offshore marine environment. It is likely that, as the time series of uninterrupted data increases, and the beach is monitored during periods of erosion (to bedrock in some locations) and accretion, a more confident interpretation on recent particle provenance may be reached.

6.4.3 The BGS surveyed the topography of Sandside Beach and estimated the sediment thickness in October 2007 Pearson *et al* (2007). A combination of terrestrial LiDAR (laser scanning) technology and mechanical sediment probes was used to estimate a total beach-sediment volume of 213,640 m^{3}. The results from the survey, shown in Fig. 6.21, indicate that most of the beach below the Mean High Water Spring tide level has a sediment cover of between 0 and 1 m.

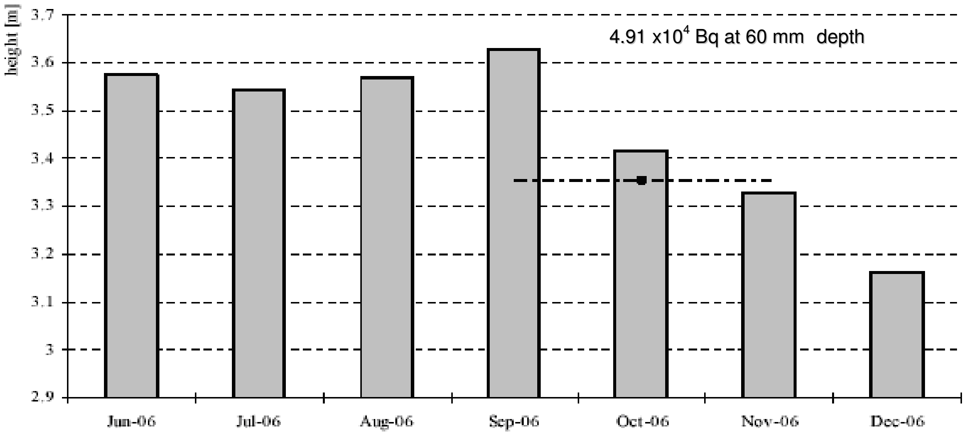

Fig. 6.19 Example of a likely particle find as a result of beach erosion

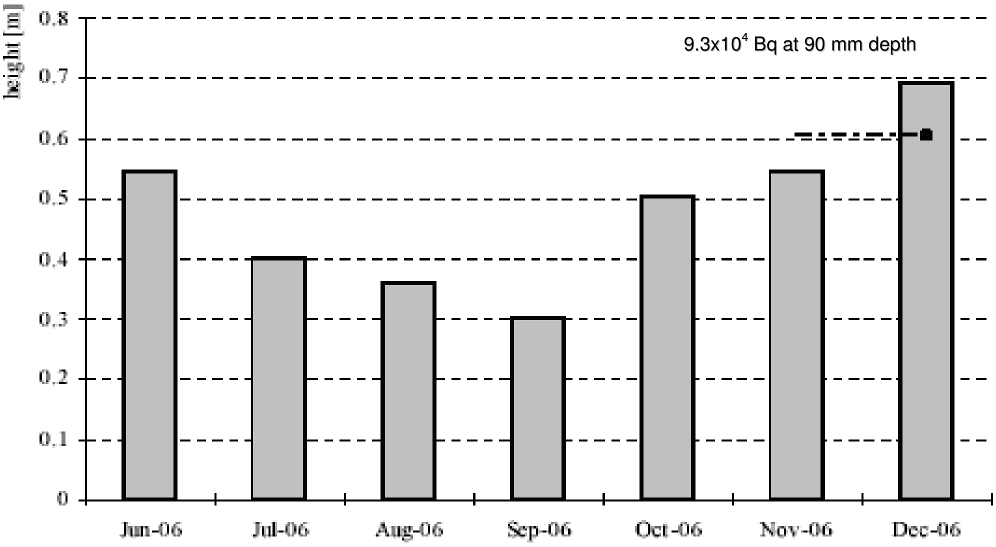

Fig. 6.20 Example of a likely particle find as a result of sediment accretion

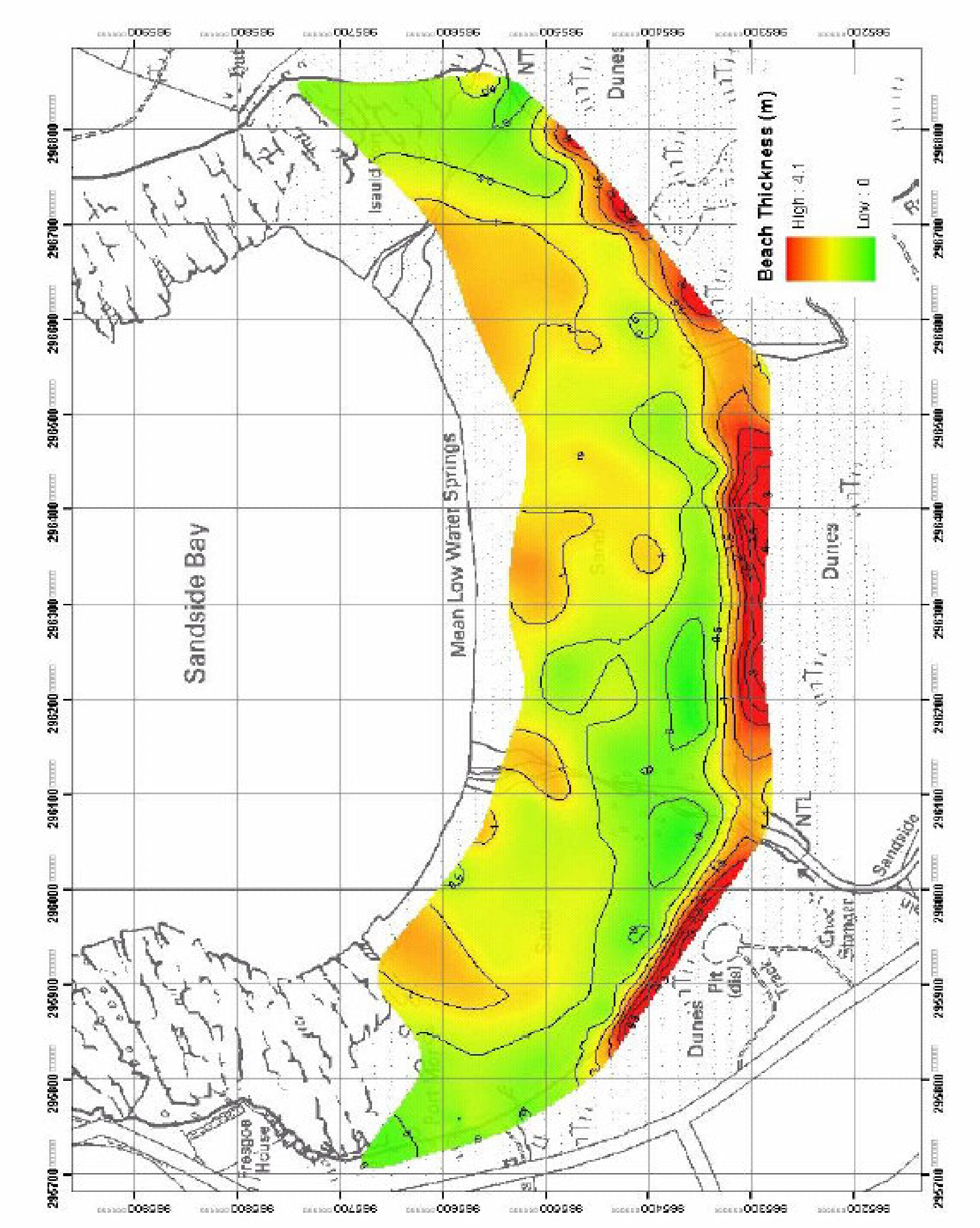

Fig. 6.21 Results from the BGS topographic survey and sediment thickness at Sandside Beach

6.4.4 By extrapolating from the data collected from the beach monitoring trials (Chapter 4), we conservatively estimate that there is a reasonable chance (probability >0.4) of the Groundhog Evolution 2 system detecting a *significant* (10^6 Bq) particle at a depth of 500 mm, and a high probability (probability >0.8) that it will detect a *significant* 10^7 Bq particle at 500 mm depth. Given a mean footprint of 217,000 m^2 (2007), we can estimate that about 65,000 m^3 of sand is being surveyed for *relevant* (10^5 Bq) particles, 87,000 m^3 for *significant* (10^6 Bq) particles and about 109,000 m^3 for *significant* (10^7 Bq) particles.

6.4.5 The gaps in monitoring of Sandside have provided an opportunity to assess whether Sandside tends to accumulate particles. As illustrated in Fig. 6.16, there are clearly times when the beach has a greater propensity to accumulate particles during periods of beach accretion, especially following storms. The potential for particle storage will depend upon the rate at which the beach is being rebuilt following erosion and the frequency and intensity with which the beach is being monitored with the Groundhog Evolution 2 systems. We know from Chapter 4, that there is a very high probability of detecting all *relevant* particles to greater than 200 mm depth and *significant* particles to at least 400 mm depth. These depths span the range of typical sand accretion (sandbar migration) across the beach. Bioturbation could result in particles being buried to a depth of up to 300 mm (Appendix 3-1) but *significant* particles would still be detected readily and it is probable that *relevant* particles would also be found. DPAG cannot rule out the potential for the beach to accumulate particles when periods of rapid beach accretion coincide with monitoring gaps that exceed the DPAG's recommended monitoring frequency. However, Table 6.6 summarises the particle finds on Sandside following extended gaps in the monitoring. Whilst all but the last set of data contribute to Fig. 6.16, all the estimated numbers of particles fall within the range indicated in Fig. 6.16 and thus there is no suggestion of a significant accumulation of particles in the surface sediments following any of the gaps in the monitoring. This suggests that there is a continual exchange of particles from the offshore to the onshore environment, the frequency of which is likely to be within the monthly monitoring period.

Table 6.6 Summary of the Particle Finds on Sandside Immediately Following Periods when Vehicular Monitoring was not Carried Out

Gap in Monitoring	Number of Months	Month Monitoring Restarted	Mean ^{137}Cs Particle Activity Bq	Mean particle depth mm	Number of Particles Detected	Number of Particles Corrected for beach area
Jan 03	1	Feb 03	5.4×10^4	130	3	6.90
May 04 - Dec 04	8	Jan 05/Feb 05	2.4×10^4	90	3	5.4
Apr 05 - Jun 05	3	Jul 05	N/A	N/A	0	-
Mar 06 - May 06	3	Jun 06	1.6×10^5	42	3	5.4
Apr 07 - Jul 07	4	Aug 07	1.5×10^4	80	2	2.9
Nov 07 - Feb 07	4	Mar 07	6.6×10^4	120	5	7.3

6.5 Estimated Number of *Relevant* Particles Corrected for Monitoring Effort

6.5.1 Table 6.5, provides a summary of the mean monthly number of particles recovered from Sandside Beach. To provide an estimate of the abundance of particles on Sandside Beach for any given monitoring month from the 2007 monitoring data, we need to correct for the annual mean footprint area (217,020 m^2) and detection capability for different particle activities. Here we will normalise the particle abundance to 300 mm depth of sand, which as Chapter 4 demonstrates is the Groundhog Evolution 2 detection capability for *relevant* particles. To provide an estimate for the *minor* particles, a uniform particle distribution with depth was assumed. The number of particles detected from within the depth from which there was an approximate detection probability of 0.9 (for each activity category in Table 6.7) was multiplied appropriately to provide the abundance estimate for 300 mm.

6.5.2 We estimate assuming that over the entire area of Sandside Beach (i.e. 318,000 m^2), there may be, on average, about two *relevant* particles within the surface 300 mm over a monthly monitoring cycle and an additional seven or eight detectable *minor* particles. Given the gap in monitoring in 2007, these estimates may be high. However, these data provide us with a better estimate of the likely monthly abundances of particles between the mean-high-water spring and mean-low-water spring tides on Sandside. These values cannot, however, be compared directly with those based on monitoring from earlier years (Table 6.5). This is because of changes in the footprint being considered and an improved detection system that enables particles to be detected at a greater depth. Taking these factors into account, we now estimate that there may have been four times the number of *relevant* particles within Sandside Beach compared with the values given in the Third Report (DPAG 2006). The implications of these revised estimates for the probability of encountering a *relevant* particle on Sandside Beach are discussed in Chapter 7. We reiterate, however, that, when these conclusions are taken with the time-series analysis described earlier in this Chapter, it is unlikely that there are more particles on the beach now than there were in the earlier years of widespread monitoring

Table 6.7 Summary of the Corrections From Mean Monthly Particle Finds to Estimated Abundances Over Top 300 mm of Beach Sand (ND = Not Detected)

Particle category	^{137}Cs Activity	Groundhog Evolution 2 2007 Monthly mean rate	Corrected to 300 mm depth equivalent	Corrected for beach area Particle Abundance
Minor	<10^4 Bq	0.50	1.67	2.5
	10^4 – $4x10^4$ Bq	1.67	2.5	3.6
	$4x10^4$ – 10^5 Bq	0.83	1.0	1.5
Relevant	>10^5 Bq	1.17	1.17	1.8
All	Total	4.01	6.34	9.4

6.6 Probability that a Detected Particle on Sandside Beach is *Significant*

6.6.1 Until March 2008 (present extent of monitoring), *relevant* and *minor* particles had been found on Sandside Beach, but for risk assessment, the question of the possibility of a particle found on Sandside Beach being *significant* needs to be considered. Two approaches, one on the basis of the distribution of activity of those particles found on the beach and the second on the basis of an offshore supply, and using mass as the determining factor for transport, are briefly presented below. The modelling described below in the first approach is based on the assumption that we have a random sample, and hence a representative one, from the population of particles present on Sandside at any time, although we know that this is not the case.

6.6.2 In the second approach, using the offshore particles, there are some substantial uncertainties and their relevance to the particles on Sandside Beach is academic but still informative. The approach is based on a simple mass/activity argument, but the particles that have been weighed are in no sense a random subset of the particles in the offshore environment and, hence, are not representative. We have only limited understanding of the transport processes that might move a particle from the offshore environment (W of the OD) to Sandside and (i) this ‘chance’ of transport, (ii) the transit time and (iii) the effect of transport on any break-up of particles and hence reduction in activity, are not included.

Activity Distribution of Finds

6.6.3 The first approach must find a probability distribution for the activity distribution of the particles found, and the log-Normal seems a reasonable candidate. Using the observed distribution of finds does present the possibility of a bias since, as we know, in the earlier years, the equipment would have been able to detect neither lower activity particles nor more active particles at depth. Fig. 6.22, below, shows the distribution of particle activities and superimposed a normal density with estimated mean 4.647 and standard deviation 0.436.

6.6.4 Nonetheless, a formal test would not reject the hypothesis that activity of particle finds on Sandside is log-normally distributed.

6.6.5 If we work with the probability model that log activity of particles found on Sandside Beach is Normally distributed with mean 4.648 and standard deviation 0.436 (from the sample of 109 particles), then we can calculate the probability of a particle found on the beach having an activity exceeding 10^6 Bq (or 6 in $\log_{10}$ activity) as 1-0.9989 or 0.0011 or 0.11%. (so roughly one in 1000 particles found could be expected to be $>10^6$ Bq ^{137}Cs). Were such a particle on the beach (even buried at depth), then the present monitoring system would detect such a particle with a probability >0.8 at 300 mm depth.

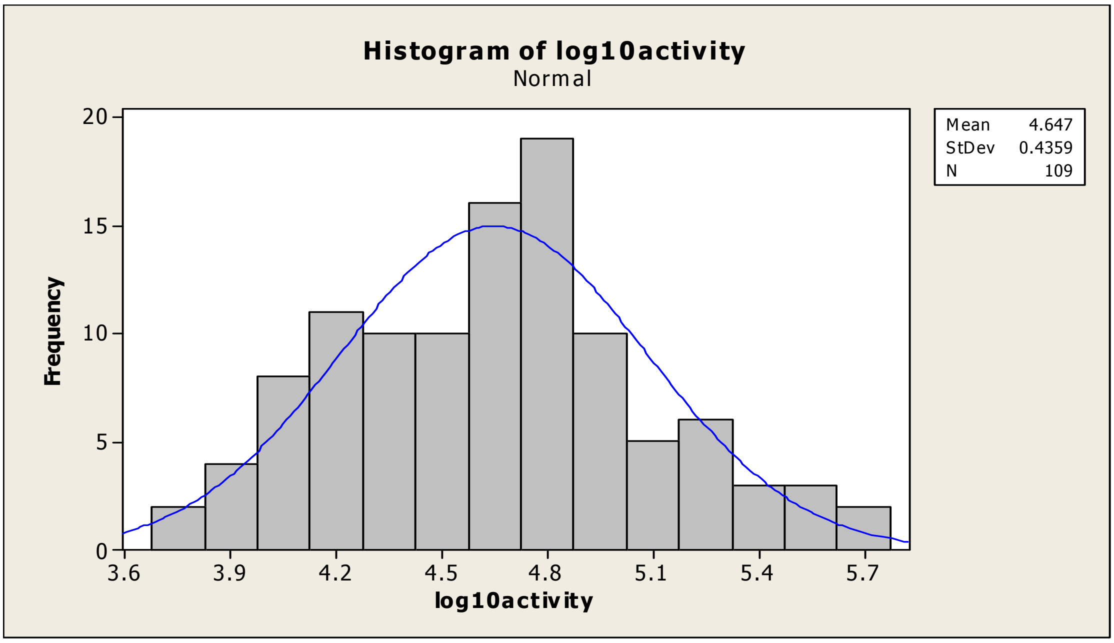

Fig. 6.22 Distribution of activity of finds

Activity Mass Relationship

6.6.6 An alternative basis for such a probability calculation can be worked through on the basis of the activity-and-mass relationship we have previously observed in our Third Report (DPAG 2006). There are 104 particles the mass of which is known, although only 11 of these come from Sandside. The remainder are from the Foreshore and offshore.

6.6.7 At a first, crude approximation, x of the y particles retrieved and weighed were $>10^6$Bq and <3.09 (log mass). This latter figure is the heaviest Sandside particle of those weighed. This is not a random sample but, if it were, from a relative frequency point of view, x/y*100% of the particles have a mass range that would make them candidates to be present on Sandside and with an activity which would be *significant*. This would be an absolute upper limit; the figure is almost certainly not valid, because of the selection procedure for the weighing.

6.6.8 A significant number of the particles above are from the Foreshore. If we were to discount them and focus on the offshore and specifically those finds to the W of the Old Diffuser (OD), which might be then considered as a potential source of particles found on Sandside, then there are 60 offshore particles. Of these 60 particles, 11 have a mass less than the largest Sandside particle weighed and an activity $>10^6$ Bq ^{137}Cs. There are 11 particles to the W or at same easting as the OD; of these, one has activity $>10^6$ Bq ^{137}Cs and mass less than the largest Sandside particle weighed.

6.6.9 If we use these figures, the proportion of the population that has mass less than the largest weighed at Sandside and activity $>10^6$ Bq ^{137}Cs, is 11/60, *i.e.* 0.18 (95% confidence interval (CI) for the population proportion is 0.09 to 0.30). If we focus only on those particles found to the W of the OD, 1/11 or 0.09 (95% CI 0.02 to 0.41) of the population would lie in this range.

6.6.10 The most recent ROV survey in 2007 identified 28 ‘hits’ to the W of the OD with maximum activity predicted as 8.6×10^5 Bq ^{137}Cs if we assumed that all of these particles have a mass less than the maximum measured for Sandside, then the above probability would be 11/88 or 0.125 (0.056 to 0.194) or 1/39 or 0.025 (with a 95% range of 0 to 0.075) if we focus only on the particles to the W of the OD.

6.6.11 If these probabilities provided realistic estimates of the probability that a particle found on Sandside was *significant*, then we would expect in 109 particles to have observed at minimum three such particles. To March 2008, none had been found.

6.7 Conclusions

Until March 2008, 109 particles have been recovered from Sandside. There has been an increase in the number of particles detected and recovered, culminating in the highest number of particles (27) being detected and recovered from Sandside Beach in 2007, despite only six months of monitoring being undertaken. These 2007 finds on Sandside were also coupled with the greatest range in particle activity and depth recovered. Since 1999, the number of *relevant* particle finds on Sandside has increased from around 0.2 (or one particle every five months) to 1.17, more than one particle per month. However, when compensating for monitoring effort (footprint) and monitoring capability (detection efficiency) and by normalising to the original Groundhog Mark 1 detection capability, there is no evidence to suggest that there has been an increase in the number of more active *minor* and *relevant* particles arriving on Sandside. Instead, Groundhog Evolution 2 appears to provide us with the best estimate of the monthly particle abundance on Sandside Beach. The mean monthly abundance appears to be of the order of 9 or 10 particles in total. Time-series analysis of all the Groundhog Evolution and Evolution 2 data indicates a seasonal variation, with a maximum occurring in the late winter/early spring months following major storms. However, were a monthly monitoring programme in operation, we estimate that, following any monitoring of the accessible area of the beach and removal of any particles detected, in the following month there are likely to be about two *relevant* particles on the entirety of Sandside Beach. It should be noted that bioturbation mechanisms operating on the beach are unlikely to move these particles to depths beyond the detection capability of Groundhog Evolution 2 (Appendix 3-1).

By analysing the number of finds following substantial gaps (>1 month) in the time series of monitoring effort, there is no evidence to suggest that there is an accumulation of particles, at least in the surface sediments. This realisation tends to support the hypothesis that there is a continual exchange of particles between the offshore and onshore environments, perhaps with a mean residence time of < 1 month, at least for those particles that remain in the surface sediments.

The probability of a particle found on Sandside beach being *significant* is estimated to be about one in 1000 based on the activity distribution of particles found. The Groundhog systems have a greater probability of detecting *significant* particles at 400 – 500 mm depth, which is likely to represent between 40-50% of the sediment volume of the beach. No *significant* particle has been detected, as of March 2008.

7. Health Implications

7.1 Insoluble Particles

7.1.1 The majority of particles examined so far can be considered insoluble, *i.e.* following ingestion, only a few percent of the ^{137}Cs and ^{90}Sr in the particle would be taken into solution. In our Third Report, (DPAG 2006) considered the potential exposure of people from coming into contact with such particles, drawing heavily on work carried out on behalf of SEPA by the Health Protection Agency, Radiation Protection Division (HPA-RPD) (Harrison *et al.* 2005). For these insoluble particles, the potentially important routes of exposure are *via* direct contact with tissue. We, therefore, considered the possible doses of radiation from the inadvertent ingestion of particles, and from direct contact on the skin and in the eye and ear. On the basis of the results we derived a three-tier system of particle classification based on the hazard that can be inferred from the ^{137}Cs content. These were as follows.

- *Significant* – fuel particles containing more than 10^6 Bq ^{137}Cs;
- *Relevant* - fuel particles containing in the range 10^5 - 10^6 Bq ^{137}Cs:
- *Minor* - fuel particles containing less than 10^5 Bq ^{137}Cs.

7.1.2 Briefly, a *significant* particle of MTR origin containing 10^6 Bq ^{137}Cs would need to be in stationary contact with the skin for a few hours for the ED_{50}[15] for acute ulceration to be approached. We considered that such contact times were credible for people spending time on beaches. More serious damage could be caused by the most active particles retrieved from the Dounreay Foreshore. A *relevant* particle of MTR origin would need to be in stationary contact with the skin for more than seven hours before any ulceration would be expected to occur. The contact time needed for the ED_{50} value to be approached was about 33 hours. We consider that such residence times on the open skin are unlikely. *Minor* particles could give rise to observable effects if held stationary for long periods in the ear but the probability of a fuel particle entering the ear is extremely low, less than one in 100 million at Sandside Bay (Smith *et al.* 2005). The classification system was based on MTR particles and took account of the major contributions to contact doses from ^{90}Sr and its decay product ^{90}Y. These radionuclides emit beta particles and cannot be detected by gamma ray spectrometry. Particles of DFR origin would give lower doses per unit of ^{137}Cs activity than those deriving from the MTR because the ^{90}Sr : ^{137}Cs ratios are lower.

7.2 The Probability of Encountering Particles

7.2.1 In our Third Report (DPAG 2006) considered the monitoring data available at that time, which related to the period up to March 2005. The Group concluded that the probabilities of encountering particles on Sandside Beach are extremely small, about one in 80 million for a *relevant* particle, with contact with

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[15] ED_{50} - the dose at which a deterministic effect would be expected to be observed in 50% of cases.

skin being the exposure pathway of importance. The probability of inadvertently ingesting a *relevant* particle was much lower, about one in one million million for a child. Since the production of the Third Report, the effectiveness of the monitoring equipment has been improved and *relevant* particles can now be detected reliably at 300 mm depth compared with the 200 mm that was previously possible. In addition, the footprint used to estimate the numbers of particles within the beach was a factor of around two greater than that used in the Third Report. Consequently, the volume of sand being considered has increased by a factor of around 3. DPAG has concluded that it is unlikely that there are more particles in Sandside beach now than there were in the earlier years of vehicular monitoring. The number of *relevant* particles present in a given volume of sand has been estimated to be about four times greater than the values given in its Third Report (Chapter 6). On this basis, the probability of a person encountering a *relevant* particle *via* contact with the skin would now be about one in 20 million, still a very small value.

7.2.2 In Chapters 5 and 6, we reinforced our previous statement that the possibility of a *significant* particle being deposited at Sandside Beach cannot be ruled out, although any predictions of when such a particle might be deposited are unwarranted. On the basis of the current performance capabilities of Groundhog Evolution 2, a *significant* particle would be detected in all cases at depths of up to 300 mm, and with a high level of probability of detection at depths of 400 mm. In order to detect and remove *relevant* and any *significant* particles promptly, we recommended that the beach should be monitored on a two-weekly basis. Over such a period, bioturbation or changes in beach altitude would probably not result in burial of a newly-deposited particle at depths of greater than about 300 mm (Chapter 6). It would, therefore, be reasonable to assume that a *significant* particle would be detected and removed the first time that Groundhog Evolution 2 passed over it.

7.2.3 A two-weekly cycle of monitoring should cover those areas of the beach that are exposed above low water and used most frequently by members of the public. These would include those areas where bait-digging is most likely to be undertaken (P.Cartwright, LRP(08) P055). We understand that a fortnightly cycle of monitoring will be implemented by DSRL at the earliest opportunity.

7.2.4 Coverage of the maximum footprint of the beach requires targeted monitoring at the times of the lowest tides, because the lower parts of the beach will only be exposed at certain times during the monthly tidal cycle and then for only short periods and under certain weather conditions. We consider that the monitoring scheme should include these areas when and where practicable, although coverage of them could take about six months to complete. During this time, however, the most readily accessible areas of the beach will have been monitored on a fortnightly basis.

7.2.5 Bait diggers are the population group most likely to come into contact with particles. If a *significant* particle were deposited on the beach at Sandside and it remained there over a two week period before being located and removed, then the probability of a bait digger coming into contact with it would be one in about 60 million. If the particle remained on the beach for 12 months before being removed, then the corresponding value would be one in about one million. The corresponding probabilities for other beach users would be less. These estimates of probability are expected to be cautious. Overall, therefore, if a *significant* particle were deposited at Sandside Beach then the chances of a member of the public coming into contact with it would be extremely small.

7.2.6 The implications of these results for the structure of the monitoring programme are discussed in Chapter 8.

7.3 More Soluble Particles

7.3.1 The dose assessment described in our Third Report (DPAG 2006) made use of data from both *in vivo* and *in vitro* experiments. A comprehensive account of the work can be found in Harrison *et al*. (2005). In most cases, the particles were relatively insoluble. In one case, however, a particle denoted MTR113 dissolved readily and extensively. About 60% of the ^{137}Cs and more than 40% of the ^{90}Sr in the particle went into solution. At a late stage in the preparation of our Third Report, we were advised that this behaviour could be consistent with particles consisting mainly of uranium oxide. UKAEA considered that such particles may remain generally intact in the slightly alkaline conditions in the marine environment, but could dissolve readily in the more acid conditions encountered after ingestion.

7.3.2 The occurrence of more soluble particles is potentially important from the dosimetric point of view because, if ingested, they represent a slightly higher long-term risk of fatal cancer compared with particles of the same activity and typical solubility. This arises because, if radionuclides were taken into solution in the gut, a proportion would be transferred to other tissues and organs within the body. Different tissues and organs have varying sensitivities to radiation, and the biokinetic behaviour in the body will depend on the radionuclide involved. All of these factors can be taken into account and the overall impact assessed *via* the estimation of the effective dose (Third Report paragraph 3.2.19).

7.3.3 In our Third Report (DPAG 2006) considered a particle having the radionuclide composition of MTR fragments and containing 10^5 Bq ^{137}Cs. If ingested by a child, a particle of typical solubility would give rise to an effective dose of about 0.5 mSv, whereas for a particle with solubility similar to that of MTR113 the corresponding dose would be a few mSv. For comparison, the annual effective dose received by a typical individual in the UK from all sources of ionising radiation is about 2.7 mSv, while in some parts of the country the average value is about 7 mSv. In both of these cases the majority of the dose arises from natural sources (Watson *et al*. 2005).

7.3.4 One of the recommendations in the Third Report was that work be undertaken to establish a best estimate of the proportion of particles of similar characteristics to MTR113 that might have been released. We suggested that some simple solubility tests using 0.01M hydrochloric acid would be sufficient for this purpose and further, that 150 particles should be randomly selected from those already retrieved. Any particles that had already been used for studies that would compromise the solubility test were rejected. UKAEA has completed the tests and reported results to SEPA and DPAG in terms of the solubility of ^{137}Cs, ^{90}Sr and uranium. The results have been summarised in Chapter 3 of this report.

7.3.5 Most of the particles released around 2% or less of the ^{137}Cs into the solution phase. These data were comparable with the earlier work done at UKAEA and NRPB and the more rigorous *in vitro* work done by NNC / SUERC and described in Harrison *et al*. (2005). A few values were in the range 3 – 4%, but we do not consider these slightly higher values to be significant from the radiological protection point of view. Three particles did, however, give higher values, the percentages of ^{137}Cs released being about 9, 52 and 75. The respective total ^{137}Cs activities in these particles were 2.6x10^4, 1.3x10^4 and 1.3x10^3 Bq. It should be noted that UKAEA considers that the second of these particles contained about an order of magnitude more ^{137}Cs activity than had been measured originally (Chapter 3). On this basis, the percentage of ^{137}Cs taken into solution from the second particle would be about 5.

7.3.6 The first and third of these three particles gave no measurable release of uranium into solution. The second had been studied by SEM EDAX and had been clearly shown to be of MTR origin. In terms of the data on uranium, UKAEA concluded that for four other particles some or all of the uranium had gone into solution but some ^{137}Cs remained with the solid residue. Consequently, there was no evidence of any of the particles studied having the overall characteristics of MTR113, where the observations were that parts of the particle matrix and the associated radionuclides went into solution.

7.3.7 If a particle having the characteristics of MTR113 were ingested, ^{90}Sr would be the largest contributor to the effective dose (Harrison *et al.* 2005). The three particles having higher solubility of ^{137}Cs are all in the *minor* category. Nevertheless, the possibility that more active particles might behave in a similar manner cannot be ruled out. For this reason, DPAG requested *via* SEPA that further analyses be carried out for other radionuclides, notably ^{90}Sr. For the three particles having higher solubility of ^{137}Cs, UKAEA measured the amount of ^{90}Sr taken into solution. The inferred values are all likely to be less than 5% when the expected true activity in the second particle is taken into account (Chapter 3).

7.3.8 Three of the particles studied showed over 5% ^{137}Cs taken into solution. We have considered whether the possible presence of such particles warrants a change in its definition of *significant*, *relevant* and *minor* particles, and, in particular, whether the lower bound for *relevant* particles should be reduced below 10^5 Bq ^{137}Cs. Such a change could then have implications for the performance criteria for monitoring of beaches, although this would be a matter for SEPA. However, in terms of the percentage solubility of ^{137}Cs, one of the three identified by UKAEA was broadly similar to MTR113 but, on the same basis, the solubility of the ^{90}Sr was much lower (Chapter 3). Using the information given in Harrison *et al.* (2005), the effective dose resulting from the ingestion of such a particle would be lower than that which would be obtained using the solubilities appropriate to MTR113. Thus, for a particle containing 10^5 Bq ^{137}Cs, the effective dose would be only a few mSv. Even if all of the ^{90}Sr went into solution after ingestion, the effective dose would be only a factor of two greater than the value for a particle with the characteristics of MTR113.

7.3.9 On this basis, we have concluded that there is no justification for changing the boundaries of its current 3-tier system. This system is based on an analysis of the composition of Dounreay particles and a detailed assessment of their dosimetry and the hazard associated with the dose. It is specific to the particles considered in this report.

8. Future Monitoring Requirements

8.1 Introduction

8.1.1 In our Third Report (DPAG 2006), we made recommendations about the frequency of monitoring of the beaches at Sandside, Dounreay Foreshore, Scrabster, Crosskirk, Brims Ness, Thurso, Melvich, Murkle, Peedie and Dunnet.

8.1.2 In its response to our Third Report (DPAG 2006), SEPA asked for commentary on the adequacy of existing monitoring, specifying that work in this area should differentiate clearly between monitoring needed for public protection, reassurance and scientific investigation. These very different objectives require different approaches in terms of the sensitivity of equipment and the time intervals between surveys.

8.2 Beach Monitoring at Sandside

8.2.1 In our Third Report, we noted that it is important for the regulator and the site operator to agree the precise objectives of the programme of monitoring and retrieval of particles at Sandside Beach (6.9.9). Our Third Report (DPAG 2006) set out the following as possible objectives:

- Providing a means by which fuel particles that are considered of radiological relevance are detected promptly and removed, *i.e.* fulfilling in practical terms the requirement placed on SEPA by the Secretary of State in 1998;
- Providing information on the numbers of such fuel particles in the beach surface within a given time period, together with their activity, thereby informing decisions on any need for changes in the intervention strategy;
- Providing reassurance to the public that the radiological hazards associated with using the beach at Sandside are very small, and that any changes in this situation would be identified promptly.

8.2.2 We consider the three-tier system of classifying particles to be helpful in assessing the potential impact of particles in terms of public health. We reiterate that a particle detection performance criterion of 10^5 Bq ^{137}Cs at a depth of 300 mm with a minimum of 95% confidence of detection (*i.e.* lower bound of the *relevant* category) provides a reasonable margin of safety.

8.2.3 Based on available data on mass and activity, we have previously stated that the possibility of a s*ignificant* particle being deposited at Sandside cannot be ruled out. Further support for this idea is set out in Chapter 6 of this report, where, on the basis of present evidence, our best estimate is that roughly, 1-in-1000 particles found could be in the *significant* category, although the timing of such an event cannot be predicted.

8.2.4 During the period between 1 January 2007 and 13 October 2007, a total of 27 particles has been located and retrieved from the beach at Sandside. Monitoring was temporarily resumed in March 2008 when five particles were found during an incomplete survey of the beach. The 2007 total exceeded the highest number found previously in any calendar year, even though there was a break in monitoring between March and August 2007. In 2007, more of the particles retrieved were *relevant* than had been the case in 2006. Of those detected in 2007, two particles were detected at depths at which they would probably have been unlikely to have been detected by previous generations of beach monitoring equipment. The range of activities detected in 2007 was greater than previous years; this may also reflect the improvement in the monitoring capability.

8.2.5 The field trials of Groundhog Evolution 2, described in Chapter 4, indicated that this equipment has a reasonably high probability of detecting *relevant* particles to a depth of 300 mm. This is around the depth of sand that might be mobilised over a 2-week period, which in turn is the current frequency of monitoring at Sandside recommended by DPAG. It is understood that UKAEA is making plans to increase monitoring frequency to match this recommendation. Consequently, a consistent programme operating on a 2-week cycle would give a reasonable chance of detecting and removing newly arrived *relevant* particles. The regulator might then consider that, in practical terms, the requirements from the Secretary of State were being fulfilled.

8.2.6 Even if a *significant* particle containing 10^6 – 10^7 Bq ^{137}Cs were to be encountered, it would be unlikely to result in long-term health consequences. The overall risk that these particles pose to human health is a combination of the hazard and the chance of encounter. Nevertheless, *significant* particles can be assumed to be undesirable hazards. Should a particle of 10^8 Bq ^{137}Cs be detected on the beach, DPAG would recommend that the beach be closed to the public.

8.2.7 The frequency of monitoring determines the maximum time that particles present on the beach may remain there, before being detected and removed. From the public health point of view, *significant* particles are of primary interest. Thus, the monitoring interval needs to be defined to ensure that, if a *significant* particle were present on the beach, it would not remain there for a sufficient period of time to pose an unacceptable risk to the public using the beach.

8.2.8 The Health and Safety Executive has suggested that a risk of death of one in one million is generally tolerable in terms of risk. We have, however, conservatively assumed that the situation would be unacceptable if the chance of encountering a *significant* particle exceeded one in one million even though this is highly unlikely to result in death.

8.2.9 From Chapter 6, the total area of Sandside between MHWS and MLWS is assumed to be 318,000 m^2 for monitoring purposes. This can be taken together with the information given in our Third Report (DPAG 2006) to estimate the frequency of monitoring that would need to be undertaken to reduce the chance of being exposed to a *significant* particle to less than one in one million.

8.2.10 Groundhog Evolution 2 has been shown to be capable (with a probability of greater than 85%) of detecting such particles to a depth of at least 400 mm (Chapter 4). Thus it would be reasonable to assume that a *significant* particle would be detected and removed the first time that Groundhog Evolution 2 passed over it.

8.2.11 The lowest parts of Sandside Beach will only be exposed for short periods at certain times during the monthly tidal cycle and access could be further restricted by weather conditions. For these reasons, monitoring of all of these parts of the beach would probably take about six months to complete (Chapter 7). All parts of the beach footprint would therefore be monitored at least once in a 6-monthly period. If a *significant* particle arrived on the lowest parts of the beach during this period and remained there, then it should be detected and removed either during that 6-month period or during the next one, *i.e.* up to about one year after it first arrived. However, during much of this period people would have only limited access to that part of the beach because it would be underwater for most of the time.

8.2.12 If a particle remained on the beach for one year then the probability of someone coming into contact with such a particle would be less than one in one million. However, this is a hypothetical situation that cannot strictly be applied to the lower parts of the beach for the reasons given above. A particle deposited in the part of the beach that is used by people would be located and removed over a much shorter period because of the much higher frequency of monitoring. The probability of an individual coming into contact with a *significant* particle would therefore be very much less than one in one million.

8.2.13 The rate at which particles arrive at Sandside Beach could change as a result of operations offshore. Targeted removal of high-activity particles from the seabed should cause a reduction in arrival rate. However, increases might occur if, for example, particles were released onto the sea-bed surface as a result of retrieval procedures or the decommissioning of the Old Diffuser (OD). Particles could also be mobilised if the FEPA Order were to be rescinded and fishing resumed. From the broad estimates of transit time made in Chapter 5, the effects of such changes offshore might not be observed at Sandside Beach until several years after they had occurred.

8.2.14 From Paragraph 8.2.12, the minimum criterion for the protection of public health in Paragraph 8.2.8 could be satisfied in principle by a scheme in which the entire beach was monitored twice yearly. In practice, to achieve this, the beach must be monitored on a much more frequent basis. We regard it as important to obtain consistent data over a substantial period in order to assess whether there are real seasonal variations in the deposition of particles on a beach. The frequency of monitoring should be compatible with changes in beach altitude. In addition, we are aware that DSRL is about to undertake operations that may lead to variations in the rate of particle deposition. For all of these reasons, we do not consider it prudent to reduce the frequency of monitoring of the beach, as a whole, to twice yearly in the immediate future. Monitoring should be undertaken at fortnightly intervals as recommended in our Third Report (DPAG 2006).

8.2.15 This monitoring frequency would result in a probability of encounter of one in 20 million per year for the most exposed person. If this monitoring frequency were reduced, clearly, the probability of encounter would increase, *i.e.* if it were decreased by a factor of 20 the probability would be around one-in-one million. However, we consider that consistent monitoring is needed to fulfil the requirements of the Secretary of State, to detect any changes in environmental condition at Sandside Beach and to provide a suitable level of protection of public health.

Recommendations

Due to the significant uncertainties in the rate arrival and offshore activities, we continue to recommend a fortnightly monitoring frequency to provide sufficient reassurance.

We reiterate the point made in our Third Report (DPAG 2006) that it is for Scottish Government, SEPA and the site operator to agree on the objectives of the monitoring programme at Sandside Bay. Factors such as the frequency of monitoring should be reviewed at appropriate times.

8.3 Monitoring of the Dounreay Foreshore

8.3.1 We consider that, given the history and recent *significant* finds on Dounreay Foreshore, the Foreshore be closed for public access with immediate effect.

8.3.2 We recommend that the Foreshore should continue to be monitored fortnightly as the data derived could provide early indication of any potential change in particle arrival and activity for other beaches. We recommend that all accessible areas of the Foreshore should be monitored, including rocky areas where sediments accumulate.

8.4 Dunnet and Other Beaches

8.4.1 We recommend that the beaches at Brims and Crosskirk should be monitored on a quarterly basis for the near future, as these beaches are the closest to the eastern side of the plume, and if particles were found here, this may indicate a change in the distribution of particles. These beaches are also accessible for monitoring throughout the year, unlike areas offshore.

8.4.2 We recommend that Melvich Beach should be monitored on an annual basis as this is the next beach W from the Dounreay site after Sandside, where particles continue to be deposited.

8.4.3 As particles have been found at these locations, the beaches at Murkle and Peedie should continue to be monitored annually while at Dunnet Beach those areas of the beach most frequented by the public should be monitored quarterly and reviewed when a habits survey has been undertaken.

8.4.4 Thurso and Scrabster beaches should be monitored annually. Although no particles have been detected on these beaches they are likely to have significant local occupancy and particles have been detected on beaches further E.

8.5 Offshore

8.5.1 We recommend that further work with the offshore ROV is undertaken to provide information on present particle distribution. This work will be vital to determine potential future changes of particle distribution that could occur due to operations including the recovery of particles from the sea bed and decommissioning of the OD.

8.5.2 We welcome developments with the ROV and the remote particle-recovery system, and its implementation once the system capability is proven. We also welcome the information from DSRL that it intends to begin offshore particle retrieval work in the near future It is consistent with Recommendation 7.8.14 on pp148 – 149 of our Third Report (DPAG 2006). This work will affect the rate of arrival of particles in the near- or long-term as particles are removed from the ' offshore plume'. In the short term, this work could mobilise particles in the sediment or particles could be 'lost' during recovery, which in turn, could result in changes in the particle occurrence on local beaches, notably Sandside. We, therefore, recommended to DSRL that a 'sentry box' procedure is followed to the W of the recovery area. An area of sea bed should be selected to the W of the OD and straddling the suspected boundaries of the W particle plume shown in Fig. 5.10. This area should be subjected to consistent monitoring with the frequency necessary to check for possible changes in the transport of particles towards Sandside Bay. The necessary frequency cannot be specified at present, and a regime of baseline monitoring will have to be devised and implemented in the near future to establish this, before the main effort of particle recovery begins. Once properly implemented, such a 'sentry box' system of monitoring should be capable of providing an early warning of any changes in the numbers or activities of particles which may later arrive on Sandside Beach. We are happy to report that this recommendation has been accepted by DSRL and will be adopted.

8.5.3 We welcome the ongoing work to characterise the state of the OD and its associated environment. We support further ROV monitoring and, if necessary, diver surveys in this regard.

9. Overview, Conclusions and Recommendations

9.1 Background

9.1.1 Our Third Report presented conclusions and recommendations for further work based on our findings to that time. The present report records the progress that has been made in the areas requested by SEPA.

9.2 Potential Future Sources of Particles

9.2.1 Major caches of particles remain both on site and off site.

9.2.2 The Shaft and the Wet Silo were repositories for swarf and contain particles expected to greatly outnumber those released to the environment. The Shaft has now been isolated from its surrounding environment and currently neither facility should be capable of discharging particles

9.2.3 A much smaller number of particles remain in the D1251 Sentencing Tanks and also in the Low Level Waste (LLW) Pits, which are not isolated from the environment. A few particles have been found in Landfill 42 but any remaining are unlikely to make a significant contribution in the offshore environment.

9.2.4 The Old Low Active Drain (LAD) seems likely to harbour particles and parts of the Non-Active Drainage system are known to contain particles.

9.2.5 The pipework leading to the ODC, the Chamber itself and the upstands could contain particles. Thorough consideration of the fissured rock surrounding the Chamber suggests that it may also contain particles, adding to the complexity of its decommissioning.

9.2.6 CONCLUSIONS: None of these sources is thought to be currently releasing substantial numbers of particles to the environment. The LLW Pits and the Old LAD are less engineered barriers than the now isolated Shaft and Wet Silo. Decommissioning of these facilities (especially the removal of disposed materials) and of the ODC will require special care in planning and execution to avoid potential release of further particles.

9.2.7 RECOMMENDATIONS: Further work should be undertaken to improve understanding of conditions in and around the ODC before proposals for its decommissioning are formulated.

9.3 Particle Characteristics and Behaviour

Density

9.3.1 The approximate density of 13 Material Testing Reactor (MTR) and four Dounreay Fast Reactor (DFR) particles has been measured.

9.3.2 No significant relationship was found between the density of particles and the points of their retrieval nor the level of radioactivity contained.

9.3.3 CONCLUSIONS: No good evidence of the contribution of density in particle transport could be deduced. It is concluded that little would be gained from further measurements.

Solubility

9.3.4 The solubility of 151 particles in hydrochloric acid (pH 2, approximating to gastric conditions) was measured.

9.3.5 Only two particles demonstrated a solubility for ^{137}Cs that was similar to MTR113 but the corresponding values for ^{90}Sr were much less, typical of other particles.

9.3.6 The solubility of uranium suggested none was composed of uranium oxide.

9.3.7 CONCLUSIONS: The likely occurrence of uranium oxide particles, of which the previously anomalous particle MTR113 might have been an example, is less that one percent when all available data are considered. Strontium-90 is a major contributor to the dose from a particle that has been ingested or inhaled and its typical solubility from the two particles having anomalous ^{137}Cs solubility implies that no change is necessary in the previous dosimetric estimates.

Transfer of radioactivity to surrounding sand

9.3.8 Laboratory studies indicate that particles can lose activity *via* diffusion into the surrounding sediment and pore water but this would only be a small contributor to decreases in the activity of individual particles in the natural environment.

9.3.9 For particles retrieved from beaches, loss of radioactivity to surrounding sand was not strongly correlated with residence time.

9.3.10 CONCLUSIONS: The findings suggest that measurements of activity concentrations in surrounding sediment will not provide reliable markers of particle residence time.

9.4 Detection Systems

9.4.1 Analysis of the performance of TROL showed the system to be capable of detecting *significant* and *relevant* particles in the sea bed, giving reasonable estimates of their activity and depth.

9.4.2 An experimental on-beach trial of Groundhog Evolution 2 showed that it is capable of reliably detecting particles containing 10^6 Bq ^{137}Cs to a depth of at least 400 mm, and has a reasonable probability of detecting particles of 10^5 Bq ^{137}Cs to a depth of 300 mm. It is also able to detect particles containing 10^3 and 10^2 Bq ^{137}Cs close to the surface, albeit with a low probability.

9.4.3 CONCLUSIONS: TROL represents a significant development in the detection of particles offshore. We have previously recommended that serious consideration should be given to the targeted removal of such particles either by divers or remotely controlled systems. TROL type systems, especially if associated with remote retrieval facilities, can make a significant contribution to that undertaking. The performance of Groundhog Evolution 2 is substantially better than that of its predecessor, not only for the detection of ^{137}Cs, but also ^{60}Co. The system's detection capability provides reasonable reassurance that *significant* and *relevant* particles carried onto the beach in a typical sand bar of 300 mm would be detected.

9.4.4 RECOMMENDATIONS: Any change in monitoring systems should demonstrate performance in the field and be independently validated. Performance should be as good as or better than its predecessor.

9.5 Extent of Contamination in the Marine Environment

9.5.1 Survey data for 2007 generated by TROL are a valuable contribution and have been combined with data from surveys in previous years.

9.5.2 CONCLUSIONS: The present estimates of the total number of particles in the main plume offshore from Dounreay are very similar to those in our Third Report (DPAG 2006), being only four to eight percent greater. However, the total number of *relevant* and *minor* particles in the Western plume extending into Sandside Bay is now estimated as about 400-500, which is about six times greater than estimated previously. The recent findings appear to confirm that a thinly populated plume of *relevant* and *minor* particles extends as far as Murkle and Dunnet Beaches to the E. A single particle detected off Red Point shows that, at least a few, *minor* particles have been transported Westwards past the mouth of Sandside Bay.

9.6 Arrival and Distribution of Particles at Public Beaches

9.6.1 Interpretation of findings for Sandside Beach is limited because of interruptions in monitoring when access to the beach for vehicular monitoring has not been allowed. Such a gap occurred in 2007 between the end of March and mid-August and from the end of October until March 2008; consequently, potentially valuable data could not be obtained. Account also needs to be taken of the improved monitoring sensitivity of Groundhog Evolution 2, the influence of major storms and the larger footprint being monitored. Nevertheless, further analysis of the available information has been undertaken.

9.6.2 CONCLUSIONS: Although the number of particles detected in 2007 is the greatest so far, the influence of the above factors implies that a cautious interpretation is necessary. When allowance is made for particles that would not have been detected by previous, less sensitive monitoring systems, the annual number of *relevant* particles seems to have been fairly constant, year-on-year.

9.6.3 Considering the in-year data accumulated entirely by Groundhog Evolution 2, there was not a substantial number of finds after monitoring resumed. This suggests that there had not been a significant accumulation of particles on the beach in the 4-5 months when monitoring did not occur. However, the data from this more sensitive system, able to detect particles at greater depths, suggest that the number of *relevant* particles per month is about 2; this is larger than previously estimated.

9.6.4 There is some evidence for seasonal intra-annual variation with more finds in the ‘winter’ period but allowance for major storms in 2003 and 2006 makes this conclusion less secure.

9.6.5 In our Third Report (DPAG 2006), we concluded that the possibility of a *significant* particle arriving on Sandside Beach could not be excluded. Based on the statistical distribution of the activity of particles found on Sandside Beach, it has been estimated very approximately that the probability of any single particle on the beach being *significant* is about one in 1000.

9.6.6 RECOMMENDATIONS: We recommend the Foreshore and Sandside Beach be monitored at two weekly intervals during retrieval and decommissioning operations and for some years, subject to review. Surveys should be undertaken of the areas between the Foreshore and Sandside Beach using the most sensitive equipment available.

9.6.7 A sentry box system is deployed to the W of the recovery area and E of Sandside Bay; this may be capable of providing an early indication of any changes in the numbers or activities of particles that may arrive on Sandside Beach.

9.6.8 Fortnightly monitoring at Sandside Beach should be undertaken for at least a year and the results reviewed by the Regulator.

9.7 Health Implications

9.7.1 It was important to establish the potential health implications if a *significant* particle were to be present on Sandside Beach. Consequently, at our request, HPA-RPD carried out an assessment of the probability of encounter with any single particle. This showed that, with a fortnightly monitoring period, as is currently recommended, the probability of contact with the particle before it was removed is about one in 60 million.

9.7.2 In response to our previous recommendation to assess the proportion of particles having overall characteristics similar to those of the anomalous MTR 113 particle, solubility tests on 151 particles provided no evidence that any did so.

9.7.3 CONCLUSIONS: Having reviewed this and other recent evidence, we concluded that it was unnecessary to change the boundaries adopted previously to classify particles as *significant*, *relevant* or *minor*. Based on the latest estimates of the number of *relevant* particles on Sandside Beach, the best estimate of the probability of direct skin contact for ‘high rate’ users is about one in 20 million per year.

9.8 Monitoring required for the Protection of the Public

9.8.1 Estimates from available data indicate that about two *relevant* particles per month might be present on Sandside Beach but any estimates of when a *significant* particle might arrive are untenable.

9.8.2 Assessment of the improved performance of Groundhog Evolution 2 showed that the system is capable of detecting *significant* particles to a depth of, at least, 400 mm and there would be a reasonably high probability of detecting *relevant* particles to a depth of about 300 mm. About 300 mm is the depth of sand that might be mobilised during a two-week period.

9.8.3 CONCLUSIONS: Our Third Report (DPAG 2006) noted that, in 1998, the then Secretary of State wrote to SEPA asking that “SEPA ensure that there is sufficient monitoring in place to ensure that any particles finding their way to the beach at Sandside Bay are promptly detected and removed”. This statement was presumably intended to be interpreted in practice according to the degree of risk entailed. We continue to consider that the removal of literally ‘any’ particle is impractical and in the case of *minor* particles is unnecessary on the grounds of radiological protection of the public. However, in practice, all particles detected are currently removed which ensures that any hazard such particles pose, however small, is removed.

9.8.4 In principle, on health grounds, given the improbability of encountering a *significant* particle, even if it were present, on Sandside Beach and of direct skin contact with a *relevant* particle, the monitoring frequency could be reduced – possibly to once or twice per year. In practice, to achieve adequate coverage, the beach must be monitored on a more frequent basis. We are conscious, however, that future operations, such as retrieval of particles from the sea bed, decommissioning of the OD and intrusion that might be permitted if the FEPA Order was rescinded, could inadvertently mobilise some particles and facilitate their seaborne transport to beaches. Consequently, we consider that it would be injudicious to change our previous recommendations for the frequency of monitoring.

9.8.5 We also recognise that, hitherto, there has never been a year in which vehicular monitoring has been permitted every consecutive month to underpin our present understanding. Further, although the risk of detriment to health would be small, a longer monitoring interval might not be regarded as fulfilling the requirement of the Secretary of State of being ‘promptly detected and removed’.

9.8.6 We recognise that regulatory, political, societal and management aspects must also be taken into account. Consequently, this report is intended to supplement our Third Report (DPAG 2006) in providing a scientific basis on which such of the judgements can be founded.

9.8.7 RECOMMENDATIONS: The Dounreay Foreshore should be closed to the public until the Regulator decides that this is of no further practical value.

9.8.8 Following on from our Third Report (DPAG 2006), we continue to recommend that Sandside Beach should be monitored every two weeks. Bearing in mind the improbability of a member of the public coming into contact with either a *significant* or a *relevant* particle in an interval of two weeks, we consider that consistent monitoring on a two-weekly cycle with removal of all detected particles within this period would fulfil, in practical terms, the requirements to promptly detect and remove particles on Sandside Beach as prescribed by the Secretary of State. This monitoring frequency should be kept under review.

9.8.9 We recommend that the beaches at Brims Ness and Crosskirk be monitored quarterly and those at Melvich, Murkle, Peedie, Thurso and Scrabster be monitored annually. At Dunnet Bay, areas of the beach used most frequently by members of the public should be monitored quarterly until a habits survey has been completed. All of the results of monitoring should be subject to review.

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Appendices

Appendix 1-1 Summary of Recommendations from our Third Report (DPAG 2006)

1. DPAG considers that UKAEA should mitigate the potential future release of particles into the marine environment by isolating the ODC.

2. The Group considers that Low Level Waste Pits should either be emptied or protected adequately from environmental impacts, including the possibility of breaching by exceptionally large waves.

3. Offshore contamination by particles should be characterised further in terms of their extent, numerical density and distribution.

4. A larger sample of the particles recovered should be characterised to determine their mass, density, shape, size, composition, chemical reactivity and radionuclide content to test assumptions made as to the behaviour of particles in the sea.

5. Further Offshore monitoring should be undertaken. This will provide information on the continuing need for beach monitoring, both in terms of its extent and frequency.

6. UKAEA should undertake further work to determine the potential number of ^{60}Co particles in the environment.

7. The Group recommends that work be undertaken to establish a best estimate of the proportion of particles of similar characteristics to particle MTR 113 that may have been released.

8. Beach and Foreshore monitoring systems deployed must be capable of detecting particles on any monitored area of activity of 10^6 Bq ^{137}Cs and ^{60}Co to a minimum depth of 300 mm. The capabilities of such systems should also allow particles with activities of 10^5 Bq ^{137}Cs and ^{60}Co or greater to be detected to a minimum depth of 200 mm and should strive to achieve a monitoring depth of 300 mm.

9. The Group considers that any new monitoring systems must be empirically validated and compared directly with their predecessor.

10. The Dounreay Foreshore should be closed to the public until the Regulator decides that this is of no further practical value. Access should be available to local beaches unless future monitoring shows significant deterioration in the current situation.

11. The beaches at Scrabster, Crosskirk, Brims Ness, and Thurso should be appropriately monitored at the current intervals. The beach at Sandside should be monitored comprehensively every two weeks. Melvich, Murkle, Peedie and Dunnet beaches should be monitored annually.

12. Monitoring of the Dounreay Foreshore and local beaches should continue until the Regulator decides that these procedures are of no further practical value.

13. In 1998, the then Secretary of State wrote to SEPA asking that *"SEPA ensure that there is sufficient monitoring in place to ensure that any particles finding their way to the beach at Sandside are promptly detected and removed".* This statement was presumably intended to be interpreted in practice, according to the degree of risk entailed. DPAG considers that the removal of literally 'any' particle is impractical and, in the case of *minor* particles, is unnecessary on the grounds of radiological protection of the public.

14. The extent of the contamination of the environment means that it is impractical to aim to return the environment to a pristine condition. Remediation options should aim to do more good than harm to the environment. DPAG recommends that serious consideration should be given to the targeted removal of *Significant* particles in the marine environment providing that this causes only minimal disturbance.

Appendix 2-1 The causes and effects of the declining integrity and efficiency of the Old Diffuser (OD) system after 1979

The integrity and efficiency of the OD system had become suspect by the early 1980s. Pumping rates of effluent deteriorated or became erratic in 1979 and it was suspected that the risers might have become obstructed.

Diving inspections in 1981 and 1982 showed that many of the risers were not discharging. In 1983 only five were working. This led to the use of a water jet lance to flush sand from the risers. Blockages were cleared by a combination of high-pressure jetting while pumping pressures of up to 10 bar were applied from the landward side.

The significance of these details of risers becoming blocked and being cleared is that none of the clearance operations appears to have restored the discharge efficiency of the system to its original levels. Either some risers remained blocked, or other factors in the system had changed over time.

At the time, UKAEA considered it a strong possibility that ruptures had occurred in the pipework within the ODC. The effluent typically had a pH of ~2 and risers grouted into the ODC roof were made from mild steel. The large pipes and the manifolds including the valves that were connected to the mild steel pipes were made from bitumen-lined spun cast-iron. It is thus possible that parts of the pipework, including the mild steel pipes that pass through the roof of the ODC (Fig. 2.5), could have become severely corroded by acidic wastes. This may have rendered it unable to withstand the high pressures applied in attempting to clear blockages. Damage to pipework within the ODC may be indicated by the following account of an inspection of the far end of the LEDT by a Remotely Operated Vehicle (ROV) in 1989.

“On reaching the seaward end of the tunnel the door of the diffusion chamber was examined and found to be closed and in good condition. With the ROV next to the door an effluent discharge was carried out. Large amounts of particulate could be seen swirling about as soon as the discharge started and the ROV was seen to be moved about by the stream. This was the case no matter which effluent pipe was discharging. This would suggest that effluent is escaping from the pipes in this area during discharges. This could be happening inside the diffusion chamber and connecting to the tunnel *via* the drain pipe below the door. Alternatively there could be leakage in the pipework just outside the diffusion chamber where it is not protected by concrete. Because of the poor visibility due to the swirling sediment during the discharges it was impossible to determine the exact liquor escape route.” (Smith 1995)

To appreciate the significance of the ROV observation, it is necessary to understand that the OD system was designed to operate as a sealed system of pipes, without any connection between the interior of the pipework and the spaces surrounding them in the ODC or LEDT. The original intention was that the tunnel would have been operated while air-filled, but this aspect of the design was modified and the system was allowed to fill with water following completion. The swirling of raised particulate matter around the ROV on the landward side of the bulkhead door indicates that the effluent discharge must either have generated excess pressure in the ODC, causing water to exit *via* the floor level drain and around the door and to stir up sediment from the tunnel floor, or a flow of effluent must have occurred from ruptures in the nine-inch pipes where they were exposed between the bulkhead wall and the end of the haunch. The loss of fluid affected all four nine-inch pipes and their respective risers. Therefore, either all four nine-inch pipes were ruptured, or some other interconnective pathway (see Appendix 2-2 below) had developed which linked all four systems and led to similar (Hoch *et al*. 2002) loss of fluid from each.

Appendix 2-2 The Interconnective Pathways

There were clear indications by 1981-3 that the rock above the ODC roof had become fissured, at least in its upper section, and that interconnections existed for flow between risers. A report entitled "Critical Review of the OD as a Potential Source of Particles Escaping into the Marine Environment" (Hoch *et al*. 2002) stated:

"The summer 1981 dive used dye tracers to determine the locations of effluent discharge onto the sea floor. ….. Dye discharges were observed from fractures in the rock outcrop as well as from the risers; the two were judged to be of equal magnitude. The pattern of dye release confirmed that discharge cross-connections existed below sea level (eight risers, rather than the expected four, were observed to discharge dye when line C was discharging)."

The same report continued:

"Further dye tests were undertaken during the May 1983 dive. Two releases from rock ~6 m S of the discharge chamber were observed; this was a different discharge location to that observed in 1981. Regardless of which line was discharging, dye releases occurred from the same five risers". The dive report also states that 'Seepages from all unblocked holes and cracks was also evident when no discharges were taking place'.

These dye tests showed that effluent was passing only through certain risers, while others were found to be blocked by probing with a rod. Effluent also discharged from rock adjacent to the risers and up to 6 m away, including from a crack as long as 4.5 m, in the sea floor, and from a hole that was >6 m from the nearest riser. The patterns of dye emergence yielded clear evidence that there was interconnectivity of effluent between risers, with up to eight risers discharging simultaneously in 1981, and all nine-inch pipes discharging through the same five risers in 1983. The risers are ~1.5 m apart and contained within an area of sea bed about 6 m NW to SE by 3-4 m SW to NE.

Further dye tests in 1997 also indicated interconnectivity between risers and the body of the rock within which the risers are sited, with dye discharging from several openings along a long horizontal fissure in the wall of a gulley adjacent to the ND structure.

This evidence shows that the bedrock above the ODC contains channelled openings that must persist over minimum distances of ~6 m, and may possibly cover distances of >12 m. These fissures clearly cross-link between risers belonging to all four of the nine-inch pipes in the LEDT, as well as between openings on the sea bed. This suggests that an explanation for the ROV observations in 1989 that is an alternative to pipe rupture: *i.e.* an open fissure system had become established which linked all four pipe systems *via* their risers, and also linked with the roof of the ODC. Whichever nine-inch pipe was used, much of the pressure within it would then have been dissipated in causing backwards flow along the other three pipes, and in discharging fluid into the ODC *via* the hypothetical linking fissure. Because it invokes only a single fissure intercepting the ODC roof as a cause of the swirling silt observed, this explanation is more conservative than the alternative of four separate ruptures in independent pipe systems. However, the hypothesis that the combination of a single pipe rupture with the fissures that the dye tests proved had already linked all four nine-inch pipes *via* their risers, cannot be ruled out. This combination might also have caused an increase in water pressure within the ODC during effluent discharge *via* any single pipe.

The satisfactory condition of the roof rocks after grouting can be inferred from figures given by Shimmin (1963) that it took between one and two weeks to drill all thirteen holes. He must have been well aware of the risks of rapid sea-water inrush, and probably would not have followed a procedure of keeping thirteen holes partially completed in the way he described had he not been fully confident that the surface layers of rock were sound. This confidence must have been based on the lack of fragmentation and inflow produced when drilling the first three riser holes. Therefore, sound, but grouted rock near the surface extended over the whole 6 m x 4 m area that now contains the OD risers. Whether its low permeability and lack of flowing fractures were wholly natural or produced by grouting, it is now impossible to say, but Shimmin's account makes it quite certain that just after completion of the OD in 1957-8 the surface rocks did not contain the cracks and fissures that dye tests proved were present in 1981-3. Therefore, fissures must have been opened within the grouted rock volume during the first two decades of operating the OD.

The origin of the fissures may be related to the nature of the grout employed, which would have been susceptible to long-term corrosion by acidic effluent. Shimmin (*op. cit.*) refers to "cement used in pressure grouting". The grout used in 1957 is likely to have been a thin slurry of Portland cement and water, possibly with some additional clay or very fine sand in the mixture although Shimmin does not mention these constituents when stating quantities used. Acids leach calcium from Portland cement, destroying the framework of calcium-hydroxy-silicates and hydroxy-aluminates that give the cement its strength. Nitric acid is especially corrosive in attacking cements (see Appendix 2-3)

Shimmin's also described drilling the first riser through the grouted rock, and stated:

"… The drilling and the rock core obtained showed excellent rock right to the sea bed. The breakthrough of the bit was very clean and there was no fragmentation of the surface layers of rock on the sea bed. The total inflow of water from the hole until the breakthrough was only 1 gallon per minute, and there was surprisingly little inflow of water to the chamber at any time. … Two further holes were similarly put through in the next few days … without incident or change of method".

"Drilling of the remaining 13 holes to within a few feet of the seabed was carried out in a similar manner, on completion of which the holes were consecutively and quickly drilled right through with a diver in attendance. "

Shimmin's account elsewhere makes it clear that there had been a 10 foot thick (3 m) layer of rock lying 41 to 51 feet (12.5 m- to-15.5 m) beneath the sea bed that possessed a high natural permeability and was connected to the sea. This layer, now recognised as a regional-scale transmissive layer was effectively sealed by pressure grouting, and did not give rise to significant inflows during subsequent drilling of the sixteen risers. Moreover, the grouted rock within a few feet of the sea bed must have had low original permeability, because no problematic inflows of water occurred during the time when thirteen riser holes were drilled to within a few feet of the sea bed. This low permeability was, however, probably acquired during the grouting, because the grout material is known to have coloured the sea water for great distances, suggesting that fissured rocks had, prior to grouting, extended to the rock/water interface.

Residual cementitious material after prolonged acid attack is soft and has no structural strength. It is more porous than the original cement paste and often undergoes cracking and shrinkage in experimental studies. Acid attack on cement grout in fractures traversed by the ODC risers would probably have softened the grout and made it susceptible to erosion by fast moving liquids during discharges. By this means a fissure may have been opened up in the riser wall. Once established a nascent fissure would have held acid that was renewed in strength with each discharge, and this would have attacked the grout. If the layer of de-calcified corrosion product cracked as occurred in experimental studies in the 1980s and 1990s, acid attack may have penetrated along the cracks themselves. Shrinkage of the cement paste may also have opened cracks between the grout and the natural rock, again allowing acid to penetrate and fresh decomposition of the grout to occur. However, propagation of an open fissure would have required the removal of the residual products of corrosion, chiefly silica gels, and this could have only occurred rapidly in places where the fluid was moving quite fast. Appendix 2-3 provides an annotated bibliography of acid corrosion on Portland Cement.

Appendix 2-3 Acid Corrosion of Portland Cement Paste

In the 1950s, Portland cement is likely to have been the base for most grout mixtures used in ground preparation. However, it was not until the 1980s that the technical literature began to describe the susceptibility of cements and concretes based on Portland cement to acid attack. Since then, new types of cements have been proposed, and the literature since 1990 contains many studies in which Portland cement paste and concrete have been used as a control in assessments of the resistance of new materials to a range of acids.

Cured Portland cement paste consists of hydration products of the calcium oxide - calcium silicate constituents of the original dry cement product. Chief among these are calcium-silicate-hydrates or CSH. These hydrates are only stable in contact with alkaline pore waters, with $pH>9$. If the pH drops below 9, they lose their calcium to solution and the structure of the hydrate collapses to form a silica gel. The solid phase in fresh Portland cement paste contains around 15% by volume of Portlandite, $Ca(OH)_2$, and the presence of this phase buffers the pore water pH to 12.3 or higher. At these high values of pH, the framework of crystals of CSH remains stable, and the paste or concrete develops and retains its full strength.

Among the strong mineral acids the rate of corrosion is ordered according to the solubility of the calcium salts in the acids. Nitric acid is the most corrosive, hydrochloric acid is intermediate and sulphuric acid is the least corrosive. Simple organic acids, such as acetic acid, corrode Portland Cement with an effectiveness between that of hydrochloric and nitric acids.

Acids in contact with Portland cement paste will attack and dissolve the Portlandite portion of the paste first. Hydrogen ions and the anions of the acid diffuse into the cement, where they react with Portlandite to form water plus the dissolved calcium salt of the acid. If the salt is soluble, it will be removed by diffusion to the surface. This process initially increases the porosity of the cement. Once all the Portlandite in the surface layer of the cement has been dissolved, the local pore water is no longer buffered at high pH, and the addition of further hydrogen ion lowers the pH below 9. This destabilises the CSH, from which Ca^{2+} ions are leached. The CSH is replaced by gels of SiO_2, $Al_2O_3/Al(OH)_3$, and Fe-oxides and $Fe(OH)_3$. Up to 50% of the mass of the cement paste is lost in solution and the porosity is greatly increased. Nevertheless the gel layer often forms a barrier to further acid attack, as hydrogen ions and the acid anions must diffuse through it to reach the unaltered cement paste. Prolonged attack lowers the pH in the outer parts of the gel to below 3, and the aluminium and iron oxy-hydroxide components of the gel dissolve away, leaving the outermost layer depleted in all constituents except silica.

The gel layer has no structural strength and is easily removed, for example by brushing, by sediment movement or by rapidly flowing liquids. It also tends to crack, and the gel may contract, losing up to 17% of its volume. These processes tend to break down the barrier to acid attack that a stable gel coat might provide, and to allow renewed access by acid to the unaltered concrete. Some acids, especially sulphuric acid and acetic acid, may promote the formation of new minerals such as gypsum and ettingite, or of calcium di-acetate, which may precipitate at the corrosion front between leached and unaltered cement paste. This expands the volume of the paste and causes mechanical spalling and cracking, which again may provide pathways for acid attack. Sea water has high concentrations of sulphate, which promotes ettingite formation, and of chloride, which promotes ettingite solubility. Thus, acid attack in the presence of sea water may be more effective than the same acid acting in a freshwater solution.

The following short bibliography is annotated with instances of acid attack on Portland cement paste and concrete.

References for Appendix 2-3

Building Research Establishment, 1991, Sulphate and Acid Resistance of Concrete in the Ground. *BRE Digest 363.*

Until 2005, this publication contained industry guidelines on acid resistance in cement and concrete. See Harrison, 1987, for a precursor publication in abbreviated form.

Building Research Establishment, 2005, Concrete in Aggressive Ground. *BRE Special Digest 1*

This publication superseded BRE Digest 363, and incorporates recent research.

Bakharev, T., Sanjayan, J. G., & Cheng, J. B. (2003). Resistance of alkali-activated slag concrete to acid attack. *Cement and Concrete Research, **33**, 1607-1611.*

Portland cement-based concrete was used as a control in a study of the effects of additives to the acid resistance of concrete. Portland cement concrete specimens lost 8% of their weight and 47% of their strength after 12 months exposure to acetic acid at pH4.

Davidovits, J. (1994). Properties of Geopolymer Cements. *In* Kiev (Ed.), First *International Conference on Alkaline Cements and Concretes (pp. 131-149),* Kiev, Ukraine: Kiev State Technical University.)

Portland cement paste was compared for acid resistance with geopolymer cements. Portland cement was completely destroyed by exposure to 5% hydrochloric acid.

Fattuhi, N.I. & Hughes, B.P. 1988. The performance of cement paste and concrete subjected to sulphuric acid attack. *Cement and Concrete Research **18**, 545-553*.

Cement pastes and concretes made with Portland cement were cast in 102 mm cubes and immersed in 2% sulphuric acid. The cubes all suffered severe corrosion and loss of weight, cement pastes losing up to 50% of weight in 50 days. The relationship between cement content and weight loss indicated that it was the hydrated phases within the cement that were attacked by the acid.

Harrison, W.H. 1987. Durability of concrete in acidic soils and waters. *Concrete*, **21**, February 1987, 18-24.

Reviews the practical implications of acid corrosion of concrete and provides recommendations for cements and concrete mixes for use in acid and sulphate-rich environments at pH>2.5. “Even if well protected, concrete is not a very suitable material to use in such conditions” (*i.e.* pH < 2.5).

Lea, F.M., 1970. The Chemistry of Cement and Concrete. Edward Arnold, London.

Mehta, P.K., 1985. Studies on chemical resistance of low water/cement ratio concretes. *Cement and Concrete Research **15***, 969-978.

Cylinders of Portland cement-based concrete lost 50% of their weight in 56 days when immersed in 1% hydrochloric acid. After six months the specimens were severely corroded. Reaction products were periodically removed during the experiment by brushing the concrete surface.

Neville, A.M. 2000. Properties of Concrete, 4th Edition. Pearson Education, Longman, Essex.

p.506-508 describes the effects of acid attack on cement paste ; p.508-514 describes the effects of sulphate attack, including the formation of ettringite (calcium-sulfo-aluminate-hydrate), which is soluble in the presence of chloride; p.514-517 describes the chemical action of sea water on concrete.

Pavlik, V. 1994. Corrosion of hardened cement paste by acetic and nitric acids. Part I : Calculation of corrosion depth. *Cement and Concrete Research **24***, 551-562.

Corrosion of Portland cement was fastest and most effective in nitric acid, followed in order by hydrochloric, formic, acetic and sulphuric acids. The relative effectiveness of corrosion depends on the solubility of the calcium salt of each acid. Corrosion rate depends more closely on total concentration of acid (held approximately constant in experiments) than on the pH which varied in the range 1 – 1.6 for HNO_3, 2.5 – 3.7 for CH_3COOH. Portland cement paste was corroded to a depth of 16 mm in 200 days by 0.1 molar HNO_3, 60 mm in one year by 0.5 molar HNO_3, with cracks appearing in the corroded layer and shrinkage of the layer by 11 to 17% of its volume.

Pavlik, V., 1994. Corrosion of hardened cement paste by acetic and nitric acids. Part II: Formation and composition of the corrosion products layer. *Cement and Concrete Research **24***, 1495-1508.

The corrosion of Portland cement by nitric acid produces a double layer of corrosion products. The white outer layer consists mainly of hydrated SiO_2 plus 2% CaO. The inner layer is brown coloured, and contains 16% Fe_2O_3 plus 3% Al_2O_3. Within this lies a thin "core layer" which contains no free $Ca(OH)_2$ (Portlandite) but otherwise consists of uncorroded Calcium-silicate-hydrates (CSH) plus elevated SO_4^{2-} content. Beneath the "core layer" the unaltered cement paste contains 65% CaO with 13% Portlandite by volume. Corrosion rate is controlled by the diffusion of H^+ and NO_3 through the corrosion products layer, and the relative thicknesses of the coloured layers depend on the diffusion of dissolved Fe^{3+} and Al^{3+} from the region in which pH<3. The Portlandite-free "core layer" is created by diffusion of SO_4^{2-} and its precipitation as gypsum or ettringite, plus outward diffusion of Ca^{2+} and OH^-.

Shi, C. & Stegemann, J.A. 1999. Acid corrosion resistance of different cementing materials. *Cement and Concrete Research **30**, 803-808*.

Cement monoliths including Portland cement were tested in acid solutions at pH3 (nitric and acetic acids) and pH5 (acetic acid only). Acid attack is by leaching of $Ca(OH)_2$ until the pH drops below 12, then removal of Ca and CaO from Calcium-silicate-hydrate (CSH). CSH decomposes at pH values below 9.

Stegemann, J.A. & Shi, C. 1997. Acid resistance of different monolithic bindersand solidified wastes. *In* Goumans, J.J.J.M., Senden, G.J. & van der Sloot, H.A. (eds) Waste Materials in Construction: putting theory into practice. *Studies in Environmental Science **71**,* Elsevier, Amsterdam, 551-652.

A Portland-cement based gel was among the control specimens in a study of the leaching of cement-encased wastes by nitric acid at pH3, acetic acid at pH3 and acetic acid at pH9. Nitric acid attack on Portland cement over a 600-day period caused corrosion to a depth of 2 mm. Deeper corrosion was inhibited by formation of a porous surface layer of silica gel where the acid had leached the calcium from calcium-silicate hydrate (CSH) which is the main solid phase of unaltered cement gel. Acetic acid at pH3 caused physical break-up of Portland cement specimens, due to formation of Ca-diacetate crystals and physical expansion of the specimen. In pH5 acetic acid Portland cement suffered complete corrosion to a depth of 10 mm in 500 days.

Stegemann, J.A., Shi, C. & Caldwell, R.J. 1997. Response of various solidification systems to acid addition. *In* Goumans, J.J.J.M., Senden, G.J. & van der Sloot, H.A. (eds.) Waste Materials in Construction: putting theory into practice. *Studies in Environmental Science **71**,* Elsevier, Amsterdam, 803-814.

Acid neutralisation tests were applied to various systems, including Portland cement. Aliquots of finely ground solid cement were reacted with different quantities of nitric acid to produce a titration curve. The behaviour of Portland cement indicates that initial leaching by acid removes $Ca(OH)_2$ which while still present buffers the system to pH12.3. Once it is removed, acid attacks the calcium-silicate-hydrates that form the bulk of the cement gel. Addition of 16 meq HNO_3/g dry cement lowers the pH to 9 with about 50% of the cement matrix having dissolved.

Zivica, V & Bajza, A. 2001. Acid attack of cement-based materials – a review. Part 1. Principle of acid attack. *Construction and Building Materials, **15**, 331-340*.

Attack by minerals acids first dissolves $Ca(OH)_2$, then attacks the Calcium-silicate-hydrates (CSH) present as the main constituents of the cement. These hydrates show progressive instability as pH is reduced from 12 to ~9. Below pH 9 CSH phases are all unstable and silica and alumina gels are the stable phases.

Zivica, V. 2004. Acid attack of cement-based materials – a review. Part 3. Research and test methods. *Construction and Building Materials, **18**, 683-688.*

Reviews the essential features that should be incorporated into test design for acid attack, and developed model equations for interpreting results. Fig. 3 is of X-ray diffraction spectra showing the loss of $Ca(OH)_2$ and $CaCO_3$ from a cement leached with acetic acid.

Appendix 2-4 Geological Assessment of the Offshore Area, Dounreay

The subsurface of the Dounreay Site, including the Offshore installations---Liquid Effluent Tunnel (LEDT), and the Old Diffuser Chamber (ODC) comprises two Middle Devonian units: the Dounreay Shore Formation (older) and the overlying Crosskirk Bay Formation (younger). The strata involved, dip at angles of up to 15^0 from the horizontal towards 330^o (N30^o W) and are transected by NNE-trending steep-to-vertical joints and faults most of which throw strata down to the ESE by a few metres (Fig. A2-4a based on the published BGS 1:25,000 Dounreay Sheet)

Onshore, extremely detailed knowledge of the rock sequence is available, as a result of work by Donovan (1980) and Michie (2006). The latter had access to onshore investigations of the Dounreay Site including deep boreholes. These have been logged both by core examination and by remote-sensing techniques, and the subsurface data so gained have supplemented geological relationships and stratigraphic sequences established by the study of natural exposures and excavations and by geophysical exploration. Onshore, the distribution of the stratigraphic units, their dip (inclination from the horizontal) and the presence of, and displacement across, faults is well established, even in areas where there are no surface exposures of rock. This is partly the result of intensive investigations, but also is possible because the original environment of deposition of the strata in extensive lakes under quiescent conditions has resulted in unusual constancy in the nature and thickness of individual beds (as little as 10 mm thick) over distances the order of hundreds if not thousands of metres. Michie (2006, p.5) established six lithofacies (rock-type associations) (A-G), (omitting an F category, for reasons that are not relevant to this report) in the local Middle Devonian strata; only four of these (A-D) exist at the location of the ODC :

Lithofacies A comprises millimetre-to-submillimetre laminae of calcium carbonate, dark bituminous mudstone and siltstone;

Lithofacies B comprises millimetre-to-submillimetre laminae of dark-brown, bituminous mudstone and siltstone. The carbonate cement within the mudstone and siltstone is often dolomitic (Ca/Mg carbonate);

Lithofacies C comprises alternating grey-to-green mudstones and siltstones and minor sandy layers < 250 mm thick;

Lithofacies D comprises assemblages of fine-to-medium grained, pale grey sandstones in layers > 250 mm thick, with thin muddy siltstone interbeds.

Where different lithofacies are interbedded on a fine (*e.g.*, a few millimetres or a centimetre) scale, they are referred to as, *e.g.* A/B.

Every lithological unit, whether comprising a single rock-type or a finely interbedded unit of more than one rock type, has been allocated a number.

Two hundred and seventeen clearly distinguished beds of these four lithofacies were established by Michie and were traced throughout the three-dimensional subsurface of the Dounreay area. Individual beds have an almost constant thickness within the area worked on, but different beds even of the same lithofacies can differ from a centimetre or so in some occurrences to a few metres in others. Given the detailed knowledge in three dimensions that has been obtained, there exists, onshore, as clear a three-dimensional picture of the distribution as could be wished of the packets of sediments identified by Michie (2006). The uncertainties in respect of the strata that exist offshore are a function of post depositional, tectonic structures that have been imposed on these rocks since they were deposited in a shallow, Middle Devonian lake ~ 380 Ma ago.

Of the four lithofacies, A and B are the most likely to be vulnerable to acid attack from liquid effluent discharges, because calcium carbonate (calcite) and calcium-magnesium carbonate (dolomite) are highly reactive to acids. All the units now identified as comprising the roof rocks of the ODC included substantial elements of facies A and / or B.

The sedimentary carbonate rocks and diagenetic cements themselves are not the only potential modes of occurrence of carbonate in the geological environment. In rocks such as those in the Crosskirk Bay and Dounreay Shore formations, the fault zones that are known to exist are characterised by brecciation and fissuring, and were probably formed where the rocks were being tectonically extended. Readily soluble materials such as carbonates commonly go into solution where the rocks that contain them as cements are compressed, and are re-precipitated in tensional zones, where they occur as veins and lenticular tension gashes. Such veins and gashes are observed in the vicinity of faults at natural rock exposures along the coast in the vicinity of Dounreay

Offshore, the disposition of the stratigraphic units and faults (Fig. A2-4a), as shown on the published (1: 25,000) British Geological Survey Sheet, is based solely on the projection offshore of known and firmly established geological relationships, onshore. The only geologists known to have examined the rocks offshore, at any time, were Mssrs G.S.Johnstone and J.E. Wright of the BGS, Edinburgh, who visited the LEDT during its excavation in December 1956, and who inspected and reported on the geological structures of the proximal section of the Tunnel, ~350m NNE from the base of the Shaft (Johnstone & Wright 1956). They were mainly concerned with structures that had promised to result in serious incursions of water during the construction of the tunnel. A report in the form of a letter to Sir William Halcrow and Partners by Dr J.E.Richey FRS in February 1956, prior to any offshore excavation of any sort, seems to have been based entirely on inspection of the rocks along the Dounreay coast.

Whereas, the projection offshore of established onshore information is acceptable in a general way, without an offshore programme of drilling and geophysics such projection could never be sufficiently precise to enable confident advice to be offered either on the detailed stratigraphic position, and therefore the lithological nature, of the rocks in which the ODC was excavated, or on the nature of the rocks intervening between the top of the ODC and the sea bed some 23 m above.

Extrapolating from the borehole sunk in close proximity to the ODC roof as part of the site investigation for the ND, the identification of the strata comprising the ODC roof shown in Fig A2-4b as extending upwards from a metre or so below Michie's (2006) stratum B26.1 perhaps as far up as his stratum A/B28 means that the top of the sequence that comprises the roof rock of the ODC is some 40 m stratigraphically below the base of the Crosskirk Formation, and thus lies within the Dounreay Shore Formation. This conclusion is at variance with the BGS published 1:25,000 geological map of the onshore/offshore Dounreay area (Fig. 2.4a). Given the imponderables involved, this is not surprising. For example, although a large NE-SW-trending fault passing through Sandside Bay is marked offshore on the BGS map and is clearly shown as later than the NNE-trending fault set, little account is taken of the possibility of other such faults. A pair of faults cropping out to the E of Dounreay, both trend almost E-W and are shown to displace NE-SW-trending faults and to bring the Dounreay Shore Formation (to the N) into contact with the Crosskirk Formation (to the S). The application of this model to the vicinity of the ODC could easily explain the disparity between the published map and the unambiguous presence of Dounreay Shore Formation, but without very detailed offshore knowledge, the BGS geologists would have had no reason for showing the offshore outcrops in any other way.

If the ODC is very close to the NNPTE Fault, as shown on the BGS 1:25,000 map, the rocks forming the roof of the ODC may well have carried a network or localised arrays of such veins and tension gashes, as well as brecciation and fissures along open joints. Such fissuring could have resulted in the widespread discolouration of the sea water above the ODC during the grouting of the rock mass following the sea water inundation during the drilling of the first pilot hole. This grout rendered the rock sound, albeit heavily impregnated with cementitious grout

Thus there were three potential sources of soluble carbonate in the ODC roof rocks through which the risers were drilled and along which acid effluent was regularly channelled: a) primary rock composition and carbonate cements; b) veins and gashes filled with crystalline secondary carbonate; c) calcium–bearing grout.

Appendix 2-5 Video Footage of Diffuser Riser No 1 (June 2007)

On 1 June 2007 a diver removed the lead plug sealing riser 1 of the OD, and a video camera was lowered into the riser (Howse 2007). A general count rate of ~5,000 cps was recorded except when the detector was positioned directly over the riser, when count rates rose to ~10,000 cps. Moving the detector slightly relative to the aperture of the riser resulted in reductions in count rate.

This count rate of ~ 10,000 cps at the top of the open riser 1, as recorded by the sodium iodide detector in its frame is similar to the count rate obtained by the diver's plastic scintillator detector at the same position over the plugged riser, both in previous years during the annual OD inspections (*e.g.* 11,900 cps in 2005, 11,000 cps in 2006), and before the removal of the plug, and with a count of 8,400 cps after replacement of plug. In 2001, prior to the capping of riser 1, the reading was 12,000 cps. If there was any detectable gamma shine from the chamber below or from the riser walls up to the seabed surface, the NaI detector should have recorded a much greater count rate than that recorded. The observation of consistent gamma readings at the top of riser 1 over the years, whether capped or uncapped is consistent with the presence of contamination at the top of the riser, probably in the rock itself (other plugged risers also show elevated cps during annual OD inspections). The absence of raised gamma dose in two extremity TLD dosimeters sent down the riser behind the camera also suggests that gamma shine from the chamber or riser walls was small or absent.

The video recording of the operation shows that when the lead plug was removed, a plume of water issued from the hole with a different refractive index from ambient sea water. This water continued to be visibly discharged from the hole for almost an hour, although the rate of flow appeared to diminish over time. When a video camera was inserted into the riser, there was an evident upward flow of fluid, indicated by the upward travel of suspended particulate past the camera, even when the camera itself was stationary. This upward flow also diminished over a period of about an hour. Oscillations became apparent during this time, with periods of several seconds. These were thought to be due to the passage of waves over the site, changing the pressure of sea water at the bed and imposing an oscillating component of flow into and out of the riser.

Salinity recordings made by a conductivimeter that was positioned alongside the gamma detector positioned over the riser showed fluctuating readings in which the normal salinity of 34.5 ppt (parts per thousand) was depressed. The first recordings were made 20 minutes after the plug was removed, and by this time the salinity was depressed to a minimum of about 27 ppt . The readings were very variable, indicating that the plume of less saline water emerging from the riser was mixing with sea water in the vicinity of the conductivity probe. It should be noted that this probe was alongside the gamma detector that was recording the elevated count rates of ~10,000cps.

Within a few minutes following removal of the plug in riser 1, divers working for UKAEA inserted a video camera and lowered it inside in stages down to a final depth of 23 m.

The purpose of this exercise was to observe the internal condition of the riser. DPAG has viewed the footage at some length[16].

The most remarkable feature is the presence of sheets of material lining the entire length of the riser. This material takes the form of pale curtain-like sheets, attached to the riser wall and floating in the current. In a few places, nearer the bottom of the riser, the material appears more solid and has the volcano-like surface topography typical of the breadcrumb sponge, *Halichondria panicea*. However, DPAG has concluded that the material is most likely to be bacterial growth rather than a sponge because it is unlikely that with the lead plug in place there would be sufficient current flow to support a sponge colony. The marine sulphur bacterium, *Beggatoa*, is a common organism known to form films on surfaces under anaerobic or low oxygen conditions.

It is clear from the luxuriant growth of *Beggatoa* that the riser has been relatively undisturbed for some time. It would also appear, however, that it is not completely isolated from the outside world. The water column contained numerous fragments of debris that are probably pieces of *Beggatoa*, possibly broken off as a result of the disturbance caused by the intrusion of the video camera. A few of the floating objects appear more structured. The quality of the film and the fact that it is in black and white make it impossible to do more than speculate on the nature of these but it is possible that they are small comb jellies (*Pleurobrachia*). Footage taken of the diver opening the riser is in colour and this shows a large number of floating objects that do appear to be *Pleurobrachia*. If there are *Pleurobrachia* in the riser, this indicates a connection with the sea sufficient to allow interchange of planktonic larvae.

An open mussel shell was first seen being carried in suspension upwards, towards the camera. Shortly afterwards the camera was left stationary for about half an hour while a change of diver took place. When the camera was moved again, the same mussel shell fell downwards into the camera field of view. It was later seen on a ledge further down the riser. Two closed mussels were found lying at the foot of the riser on a disk-shaped structure which could be the old plug. Marine biology surveys have recorded the presence of the horse mussel *Modiolus modiolus* in the offshore environment of Dounreay. It is likely, therefore, that the mussels found in the riser and on the plug at the bottom are of this species. It is possible that the ones at the bottom were alive. One suggestion to account for the presence of the mussels at the bottom of the riser is that this riser may be connected in some way to a freshwater upwelling. However, unlike the more familiar edible mussel, *Mytilus edule*, *M. Modiolus* is not tolerant of reduced salinities.

An alternative explanation for the presence of the mussels seen at the bottom of the riser is that they were dislodged from somewhere near the surface during the investigation process. Riser 1 was originally blocked in 1995 using two lead plugs because the first one to be installed was too small to make a firm fit in the hole. A second, larger plug was therefore used above it. It is possible that the loosely-fitting lower plug was disturbed when the second plug was removed in 2007, and fell to the bottom of the hole. As it fell, the plug would have disturbed the fronds of *Beggatoa*

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[16] DPAG is grateful to Dr David George of the Natural History Museum for his comments on the video footage.

attached to the wall, and this would account for the very high numbers of fragments seen suspended in the water.

The numbers and concentrations of these suspended particles gradually reduced during the 2.5 hours that the video camera was present in the hole. Their movement initially showed a strongly rising current within the riser, but this weakened over the first 45 minutes, and as it weakened it showed oscillating behaviour that was consistent with the expected effects of waves passing at the sea surface above the site. The apparent current in the riser is most likely be the result of the initial mixing of water, especially if there is freshwater contamination (which will affect density), of passing waves, and of movements generated by the camera.

DPAG concludes from the apparent presence of *Beggatoa* that conditions within the riser had been undisturbed for some time and that there had been little interchange with the outside world. *Beggatoa* will not tolerate the high levels of oxygen that would be expected if there were full connectivity with the main seawater column. The growth of *Beggatoa* is so thick that it is not possible to see the wall of the riser except in a few places where there appears to be exposed rock and/or concrete.

A short distance above the lowest point reached in the riser, the video shows that the diameter becomes abruptly wider. This wider section is quite short, possibly as little as a quarter of a metre, but it is difficult to judge because the images contain no objects that can be used for scale. At the lower end of this enlarged section, the diameter narrows abruptly and there is a change in the form of the encrusting material on the walls from the frond- or curtain-like sheets of *Beggatoa* to the more rounded forms that were noted above as possibly resembling the breadcrumb sponge, *Halichondria panicea*. Just above this transition, a circular, annular-like structure is visible, resembling a circular ledge running around the circumference of the hole, with a distinct rim at its inner edge. This may represent the top of the original lining tube that was installed in the lowest 3 m of the hole, and the annulus of cement grout around it. Below this, the camera was lowered for some distance through a narrow, heavily encrusted, section of tube until finally reaching a flat, circular structure, on which two mussels were resting, as described above. This may have been the missing lead plug.

The original engineer’s report (Shimmin 1963) mentions that the sections of the riser holes that were left open through bedrock were drilled to a nominal diameter of 3 inches (see 2.3.1), whereas the liner tube in the lowest 3 m of each hole had an internal diameter of three-and-a-half inches. For a lead plug intended to block a three-inch hole to have fallen all the way to the bottom, the bedrock section must have been enlarged so that its present diameter is greater than three inches (>75 mm). However, it is not possible to estimate the actual diameter from the video images because of the lack of any object of known size to act as a scale. Nevertheless, the diameter of the riser appears larger through most of its depth than the internal diameter of the annular rim seen where the encrustation changed from fronds of *Beggatoa* to more rounded, sponge-like forms. If this rim represents the remnants of the original iron liner pipe, then its internal diameter should be around three-and-a-half inches, which provides a lower bound for the diameter of the main length of riser.

In a subsequent video record of riser 1 the *Beggatoa* were reported as being dead.

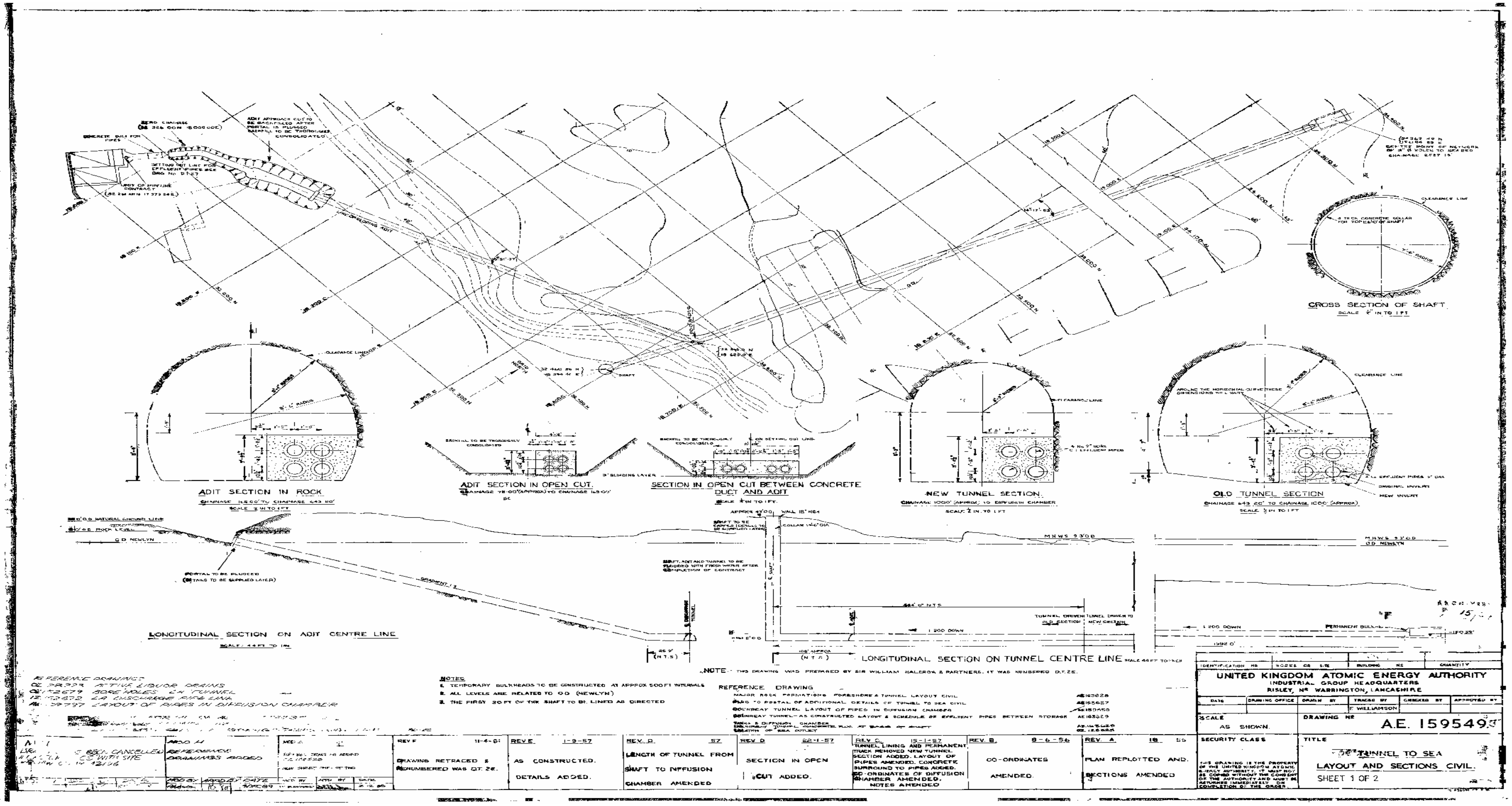

Fig. A2.1a The original engineers drawing of the OD system

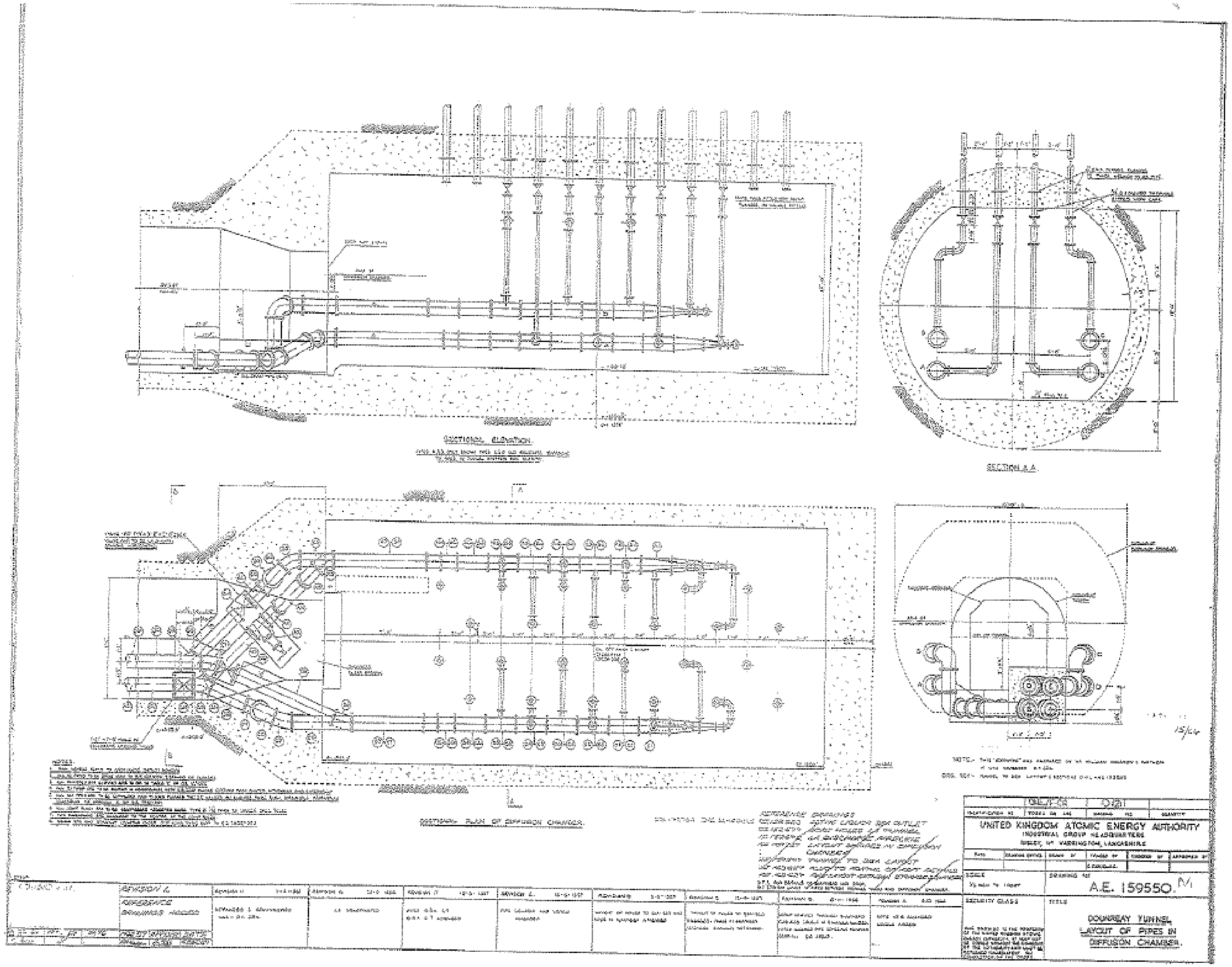

Fig. A2.1b Engineers' drawings of the ODC and the configuration of the pipework contained within it (Drawing Number AE 159550)

Appendix Fig. 2-5-8

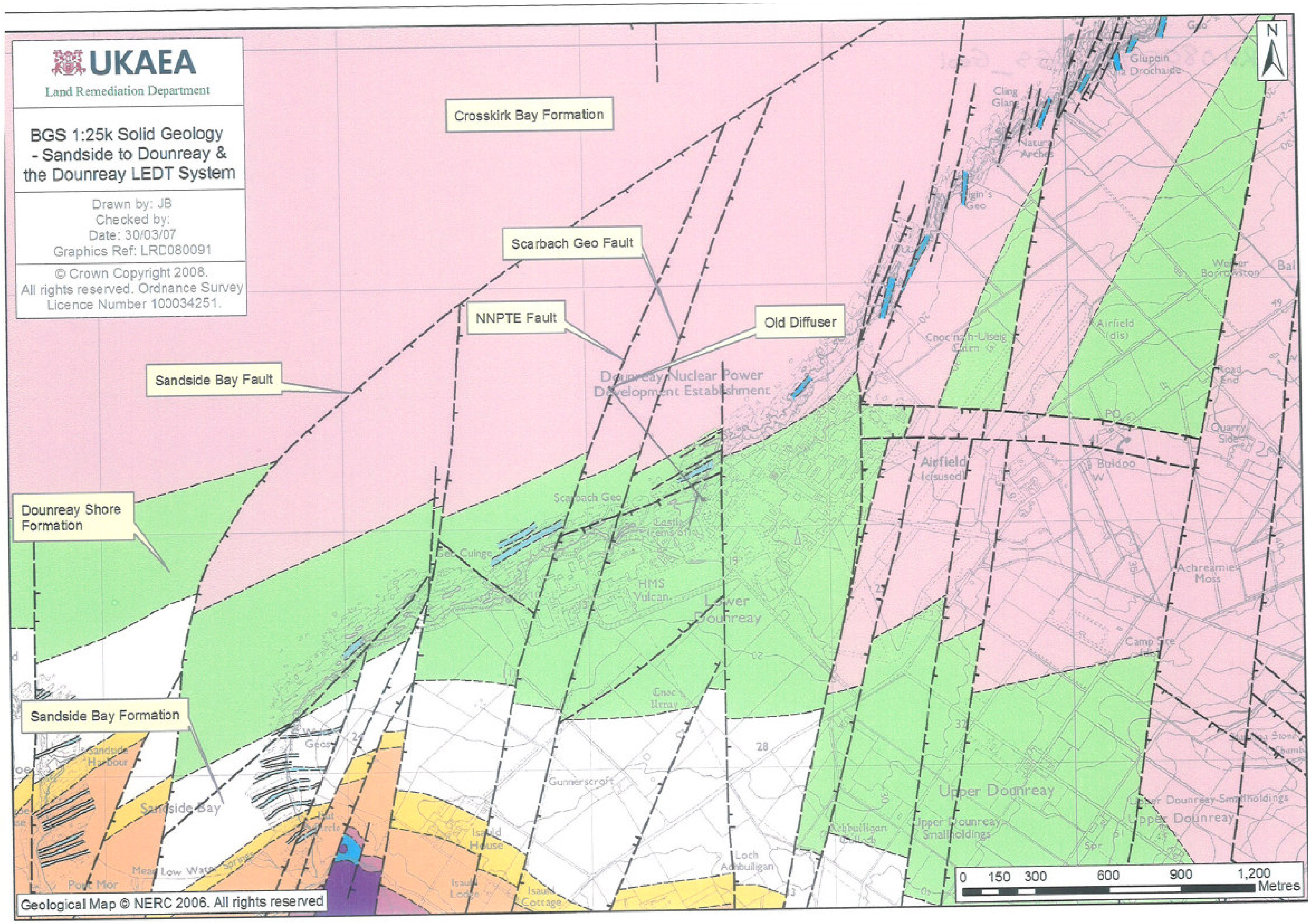

Fig. A2.4a Map (1:25,000) of the onshore and offshore solid geology slightly modified from the BGS 1:25,000 geological (Dounreay) sheet

Appendix Fig. 2-5-10

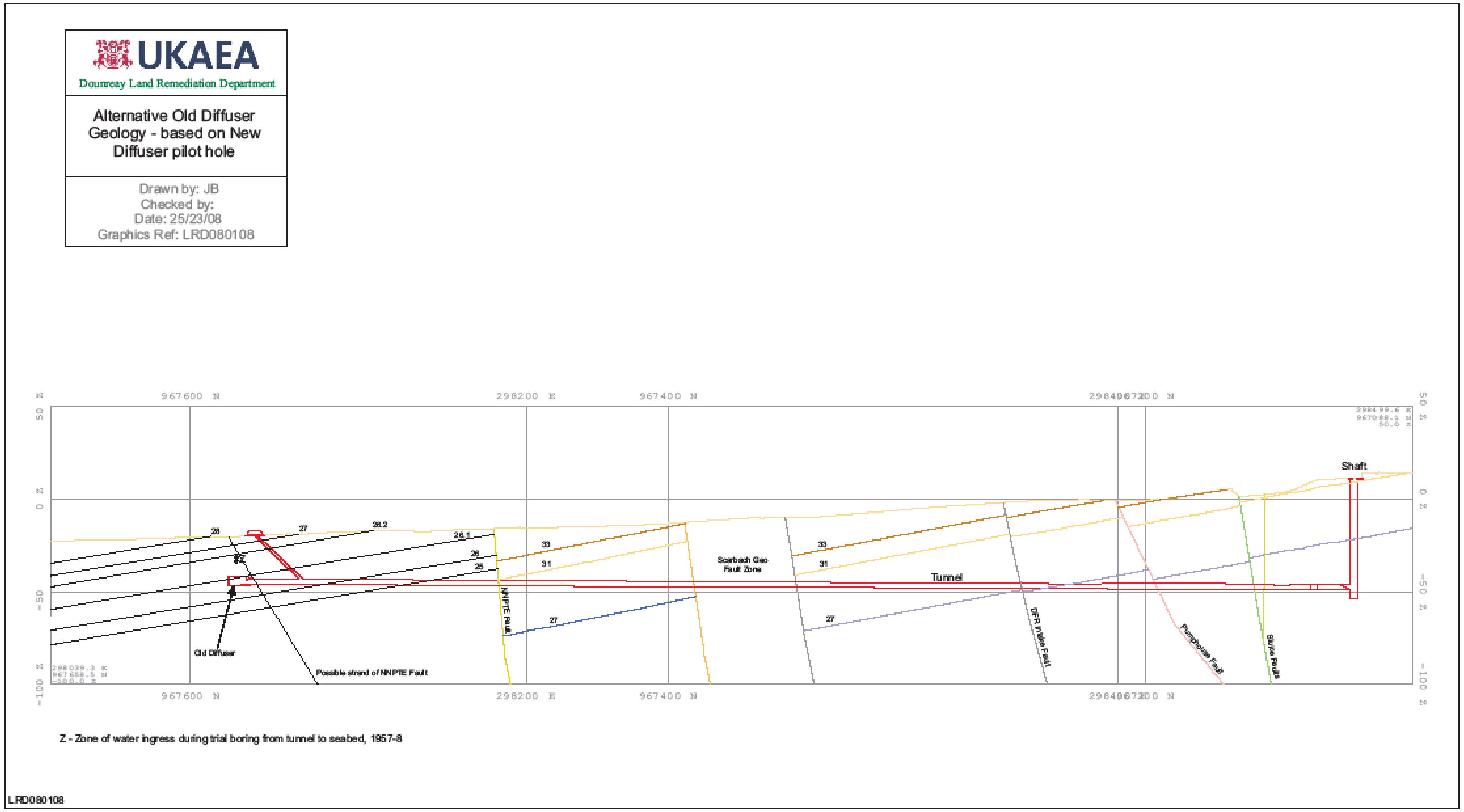

Fig. A2.4b Geological section in the vertical plane containing the shaft and the tunnel. Exact position shown for the NNPTE Fault is conjectural. Fig. 2.12 shows an alternative position

Appendix Fig. 2-5-12

Appendix 3-1 The Effect of Bioturbation on the Distribution of Particles at Public Beaches

The spatial distribution of particles in the marine sediments in the intertidal and subtidal waters around Dounreay is mainly dictated by the water movements in the area as described in paragraphs 4.4.9 – 4.4.43 of our Third Report (DPAG 2006). However, spatial distribution vertically within a body of sediment may also be influenced by the activities of animals living within the sediment – *i.e.* there may be a bioturbation effect. This could result in particles being drawn down into the sediment to a depth of more than 10 centimetres, followed in time by a return to the surface.

It is well established that deposit-feeding macrofauna can have profound effects on sediment stability (Boaden and Seed 1985, p. 73). Sediment turnover rates may be considerable. For example, it has been calculated that dense populations of polychaetes can process up to 2500 kg m^{-2} per annum.

In 2004, UKAEA commissioned a Littoral and Sub-Littoral Baseline Report by SAMS Research Services Ltd as part of its Site-wide Environmental Statement. The report states that ‘all the sandy beaches visited were typically wave-exposed beaches with little evidence of benthic infauna, with the exception of Dunnet Bay which had many lugworms (*Arenicola marina*) over the entire intertidal zone. This species is not mentioned with regards to Sandside Bay although it is known to occur there and, indeed, supports bait digging.

Arenicola is undoubtedly a cause of bioturbation and the presence of lugworm beds has implications for the detection of particles in the intertidal zone. If a beach is heavily worked by bait diggers, the human bioturbation would result in such a particle being disturbed further and possibly removed from the site on spades or on/in the lugworms. *Arenicola* does not usually extend far down the shore into subtidal regions so the main area of concern is the intertidal.

Arenicola is present in sufficient numbers on the lower shore at Sandside Beach for bioturbation to have a significant effect on sediment movement. As the bottom of the burrow may be at 200 - 300 millimetres, it is possible for material to be re-circulated down to this depth. However, this is still within the detection capability of Groundhog Evolution 2 for *Relevant* particles.

It is unlikely that lugworms would accumulate particles, as opposed to re-distributing them and it is not considered necessary to revisit the conclusions on the likelihood of a bait digger encountering a particle. However, the process of bioturbation does add a further complication to the already complex pattern of particle movement and distribution on the beach, making it impossible to predict particle movements with any accuracy.

Appendix 3-1-2

Appendix – 4 Biographical Details of Current Members

PROFESSOR KEITH BODDY CBE (Chairman)

Professor Boddy gained his PhD from the University of Glasgow and Doctorate of Science from the University of Strathclyde. He was awarded an Honorary DSc by De Montford University and is a Fellow of The Royal Society of Edinburgh; Fellow of Institute of Physics and an Honorary Fellow of: Institute of Physics and Engineering in Medicine; British Nuclear Medicine Society; British Institute of Radiology; Society for Radiological Protection; European Federation of Medical Physics.

He was formerly: a Lecturer/Senior Lecturer, Scottish Universities Research and Reactor Centre and Head of Health Physics and Nuclear Medicine Unit; Professor and Head of Regional Medical Physics Department and Regional Radiation Protection Adviser, Northern Regional Health Authority, and Head of University Department of Medical Physics, Newcastle University.

He was a Member of: Radioactive Waste Management Advisory Committee (RWMAC); Committee on Medical Aspects of Radiation in the Environment (COMARE); Ionising Radiations Advisory Committee (IRAC).

Professor Boddy is also the former President of: Institute of Physics and Engineering in Medicine; Hospital Physicists Association; International Organisation for Medical Physics; International Union for Physics and Engineering in Medicine.

PROFESSOR TIM ATKINSON (Member)

Tim Atkinson is Principal Research Associate and Honorary Professor of Environmental Geoscience at University College London and a Visiting Fellow at the School of Environmental Sciences, University of East Anglia, and at the School of Civil Engineering and Environment, University of Southampton. He directs UCL's Groundwater Tracing Unit and was Founding Director of the Bloomsbury Environmental Isotope Facility. His research contributions have ranged across the disciplines of hydrology, hydrogeology, geomorphology, Quaternary geology, palaeo-climatology and geochemistry. He has a BSc and a PhD from the University of Bristol, is a Chartered Geologist and Fellow of the Geological Society of London, and a member of COMARE.

PROFESSOR ALEX ELLIOTT (Member)

Professor Elliott graduated with a BA with first class honours in Physics from the University of Stirling. He gained a PhD in the Faculty of Medicine from the University of Glasgow and a DSc in the Faculty of Science, University of Glasgow.

He is currently the Director of the West of Scotland Health Board Department of Clinical Physics and Bioengineering, Glasgow, and Professor of Clinical Physics, University of Glasgow. He is the Deputy Lead R&D Officer for West Glasgow Hospitals and is the current Chairman of COMARE.

PROFESSOR ANTHONY HARRIS (Member)

Professor Harris graduated BSc (1956) and PhD (1959) at the University College of Wales, Aberystwyth. He is: a Chartered Geologist; Fellow of the Royal Society of Edinburgh; Fellow of the Geological Society of London and Senior Fellow of the

Geological Society of America; Emeritus Professor of Geology, University of Liverpool; Distinguished Visiting Fellow, University of Cardiff and Research Associate, National Museum of Wales.

He was formerly a Principal Geologist of the British Geological Survey, Edinburgh; Professorial Head of Department of Earth Sciences and Dean of the Faculty of Science, University of Liverpool; President of the Geological Society of London; a member of RWMAC (Radioactive Waste Management Advisory Committee) and a non-executive Director of the British Geological Survey.

PROFESSOR MARIAN SCOTT (Member)

Professor Scott is Professor of Environmental Statistics at the University of Glasgow where she is currently Head of Department. She is: European Director, International Environmetrics Society; past Chair of Royal Statistical Society, Environmental Statistics Section; Advisory Editor, Wiley Statistics in Practice book series, and a Trustee of S.P.R.U.C.E. She is also a Fellow of the Royal Society of Edinburgh.

She has served as advisor on several occasions to the International Atomic Energy Agency, was co-author of the ICRU report “Sampling for radio-nuclides in the Environment” and serves on the editorial board of the Journal of Environmental Radioactivity.

DR ANDREW TYLER (Member)

Dr Andrew Tyler is a Reader in the School of Biological and Environmental Sciences at the University of Stirling. He specialises in the development of monitoring and remote sensing systems for the detection and impact assessment of environmental radioactivity, and the use of radionuclides as tracers for environmental processes. Dr Tyler operates an ISO17025 accredited environmental radioactivity laboratory and is the Convenor for the International Electrotechnical Commission Working Group – Measurements of Environmental Radiation (IEC/TC 45BWG5).

In 2003, Dr Tyler was invited to join UKAEA’s Beach Monitoring Steering Group (BMSG), to provide impartial advice on the next generation of beach monitoring equipment. He is also an Editorial Board Member on the international journals: *Water Air and Soil Pollution* and *Water Air and Soil Pollution Focus*.

PROFESSOR LYNDA WARREN

Lynda Warren is Emeritus Professor of Law at Aberystwyth University. She has postgraduate qualifications in marine biology and marine law and policy. She was a Member of the UK Government’s Radioactive Waste Management Advisory Committee (RWMAC) and is a Member of the Committee on Radioactive Waste Management (CoRWM). She is a Member of the Royal Commission on Environmental Pollution and a non-executive Director of the British Geological Survey. She Chairs the Wales Coastal and Maritime Partnership and is Deputy Chair of the Joint Nature Conservation Committee. She undertakes consultancy work on nuclear law and policy for IDM (Integrated Decision Management) a consultancy specialising in the provision of strategic advice on nuclear matters.

DOCTOR BERNARD WILKINS (Member)

Dr Wilkins joined the National Radiological Protection Board (NRPB)* in 1973, having obtained his degree in Chemistry at the University of York and completed his doctoral research in Physical Chemistry at the University of Sussex. He is currently Leader of the Environmental Investigations Group. Since joining NRPB, he has undertaken a wide range of applied research dealing with radionuclides in the environment. For example, he was heavily involved in the response to the Chernobyl accident in 1986 and in 1998 led the NRPB's part in the response to the discovery of contaminated feral pigeons around Sellafield in Cumbria.

Dr Wilkins has contributed to the work of the COMARE sub-group on Dounreay particles since the early 1990's. Following the discovery of such particles on the seabed, he contributed to the assessment commissioned by SEPA that was published in 1998. He coordinated the subsequent work commissioned by SEPA that has since been published as a series of reports on the Agency's website.

**NRPB became part of the Health Protection Agency in April 2005*.