Vol. 34 No. 1 2016

UNDERWATER TECHNOLOGY

2nd European Conference on Scientific Diving Special Issue

ISSN 1756 0543

SUT
Society for Underwater Technology
www.sut.org

UNDERWATER TECHNOLOGY

ISSN 1756 0543 (print)
ISSN 1756 0551 (online)

SUT Society for Underwater Technology

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doi:10.3723/ut.34.001 Underwater Technology, Vol. 34, No. 1, pp. 1–2, 2016 www.sut.org

The European Scientific Diving network's 2nd Conference on Scientific Diving: a collective view from the organising committee

The sun is shining bright and it is a warm spring day in the small village of Fiskebäckskil by the Gullmar Fjord on the Swedish west Coast, where the University of Gothenburg's marine infrastructure, the Lovén Centre – Kristineberg, is situated. This is also the scenery for the 2nd Conference on Scientific Diving, which this year is hosted by the Lovén Centre from 9–11 May 2016. Over 90 researchers from 18 countries have gathered to present their research generated using scientific diving as a research tool and to network, exchange ideas and plan new initiatives. Compared to the 1st conference, held in Stuttgart the previous year, the number of participants and represented countries has doubled. The scientific talks are excellent, discussions inspiring, and they show how important scientific diving is in order to conduct underwater science, especially in coastal and other shallow aquatic environments.

This year's conference featured one poster session and four oral sessions:

- Coastal research using scientific diving – from micro to macro;
- Underwater archaeology;
- New technologies and methods for scientific divers to improve underwater research; and
- Research in cold waters using scientific diving.

The presentations expressively showed the broad spectra of research fields in which scientific diving is used, covering fields such as marine microbiology, ecology, geology, oceanography, chemistry and archaeology, across a diversity of environments ranging from the Dead Sea to the Polar regions.

The first keynote talk was given by the marine microbiologist and field scientist Dr Miriam Weber who, among others, expressed the importance of the scientific divers as 'Ambassadors for the oceans and freshwaters'. These environments are not accessible for most people and are therefore more vulnerable to anthropogenic impact, mainly because changes are not easily observable and thus not well understood. To collect more comprehensive knowledge about the natural environment and our cultural heritage, we need to be able to observe, monitor and conduct empirical studies in-situ, and not only in controlled laboratory environments. Human hands and eyes still far surpass many instruments when it comes to looking for details in the underwater environment. Traditionally, the importance of scientific diving as a research tool has not been highlighted enough, and therefore the support from governmental institutions and research funding has been negligible. Through these international conferences, researchers can establish the significance of scientific diving and set their footprint in underwater science.

The 3rd Conference on Scientific Diving will take place in Funchal on Madeira, Portugal next year (22–23 March 2016). The hope for the next conference is that the positive trend will further expand the European Scientific Diving community, that new initiatives for underwater sciences will develop, and that new technology and methodologies will be shared to support science in the underwater environment now and in the future.

Dr Maria E Asplund

Dr Maria E Asplund's research focuses on marine bacteria, trophic interactions and climate change. She has worked with scientific diving since 2004 and is the Swedish representative in the European Scientific Diving Panel (ESDP). At the Lovén Centre, University of Gothenburg, she is responsible for the development of the scientific diving and is the course leader for PhD student courses involving scientific diving techniques. She is also employed as post-doctorate fellow at Stockholm University.

Dr Pia Engström

Dr Pia Engström works in marine biogeochemistry. Her main research interest has been the marine nitrogen cycle focusing on anammox and denitrification. She currently works as a research engineer at the Lovén Centre, where she is involved in pelagic monitoring projects and is responsible for laboratories and analytical equipment. She is also member of the dive team at the station.

Claudia Klages

Claudia Klages works as an administrative assistant at a primary school and as a cleaner at the the Lovén Centre. Before she moved to Sweden, she worked at the Alfred Wegener Institute for Polar and Marine Research in Germany for more than 32 years. Among several other responsibilities, she has been involved in planning, coordination and organisation of national and international workshops and conferences.

Marie Moestrup Jensen

Marie Moestrup Jensen is a marine biologist and communications officer at the Lovén Centre. Marie is responsible for the public outreach activities at the Lovén Centre – Kristineberg, summer schools for high school students and internal communication. She is also a web editor for the Lovén Centre's website, and was responsible for the European Conference on Scientific Diving 2016 webpages. Since September 2016, Marie is on leave from the Lovén Centre and has moved to Seattle, USA.

Delia Ní Chíobháin Enqvist

Delia Ní Chíobháin Enqvist is a maritime archaeologist at Bohusläns Museum's commercial archaeology unit in Uddevalla. Since 2015, she is also a PhD candidate of the Graduate School of Contract Archaeology (GRASCA) at Linneaus University in Kalmar, Sweden. Her project will research how maritime archaeology and its results can be communicated to a diverse public with the use of new technologies. The goal of this research is to identify new ways of communicating her findings on submerged archaeology that are socially relevant to the general public.

doi:10.3723/ut.34.003 Underwater Technology, Vol. 34, No. 1, pp. 3–10, 2016 www.sut.org

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Technical Paper

PROTEKER: implementation of a submarine observatory at the Kerguelen Islands (Southern Ocean)

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Received 17 July 2016; Accepted 20 September 2016

Abstract

In the context of global climate change, variations in sea surface temperature, sea level change and latitudinal shifts of oceanographic currents are expected to affect marine biodiversity of the sub-Antarctic islands located near the polar front, such as the Kerguelen Islands, particularly in coastal waters. Sampling sites of previous oceanographic programmes focused on the Kerguelen Islands were revisited during three scientific summer cruises aboard the trawler *La Curieuse* (2011–2014). Among 18 coastal sites explored using scuba diving, 8 were selected for monitoring, as representative of the Kerguelen sub-Antarctic marine habitats, to be progressively equipped with sensors and settlement plots. Remotely operated vehicle (ROV) observations and beam trawling (at 50 m and 100 m) have also been used to contextualise them. Eight sites – in the Morbihan Bay (4), and in the north (2) and south (2) of the Kerguelen Islands – are now monitored by photo and video surveys, with temperature loggers installed at 5 m and 15 m depth, and settlement plots at about 10 m depth. Temperature data have been recovered yearly since 2011 at some sites (those equipped first). Biodiversity found on settlement plots will be characterised yearly by metagenomics. The often harsh conditions at sea involve using robust underwater equipment and simple investigation techniques and protocols to ensure the permanence and the reliability of the equipment installed.

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Keywords: sub-Antarctic, climate change, frontal shifts, coastal habitats, benthos monitoring, thermo-recorders, settlement plots

1. Climate change and the sub-Antarctic islands

The sub-Antarctic islands are those islands of the Southern Ocean north of and adjacent to the Antarctic convergence, or the polar front, a geographic situation which gives them particular climatic, oceanographic and biogeographic features (Table 1). Studies undertaken at the Prince Edward Islands in the Indian sector of the Southern Ocean have all reported a rise of over 1 °C in sea surface temperature since 1949 (Mélice et al., 2003; Ansorge et al., 2009; Ansorge et al., 2014). Over the same time period, a decrease in rainfall, an increase in extreme events and in wind speed, and an annual rise of the sunshine hours have been observed since the 1950s (Smith, 2002; Mélice et al., 2003; Le Roux and McGeoch, 2008).

It has been proposed that such climate changes correspond in time to a southward shift of the Antarctic circumpolar current (ACC) and in particular its frontal systems, the sub-Antarctic front and the polar front, in between which the islands are located (Allan et al., 2013). Recent observations indicate that this highly dynamic region is undergoing

Table 1: Sub-Antarctic islands located north of and adjacent to the polar front.

Islands	Geography	Administration
Antipodes Islands	49°67'S 178°77'E	New Zealand
Auckland Islands	50°42'S 166°05'E	New Zealand
Bounty Islands	47°42'S 179°04'E	New Zealand
Bouvet Island	54°26'S 03°24'E	Norway
Campbell Island group	52°32'S 169°08'E	New Zealand
Crozet Islands	46°25'S 51°59'E	France
Diego Ramírez Islands	56°30'S 68°43'W	Chile
Falkland Islands	51°42'S 57°51'W	United Kingdom; claimed by Argentina
Heard Island and McDonald Islands	53°00'S 73°00'E	Australia
Kerguelen Islands	**49°15'S 69°35'E**	**France**
Macquarie Island	54°37'S 158°51'E	Australia
Prince Edward Islands	46°46'S 37°51'E	South Africa
Snares Islands	48°01'S 166°32'E	New Zealand
South Georgia and South Sandwich Islands	54°17'S 36°30'W	United Kingdom; claimed by Argentina
Tierra del Fuego (islands associated with)	54°00'S 70°00'W	Chile and Argentina Boundary, treaty of 1881

change in response to a warming climate. Climate change impacts on those islands are varied, and are both direct and indirect: glacier retreat, temperature increase as well as decrease in precipitation, generating favourable conditions for introduced species and marine biodiversity modification (Smith, 2002; Pendlebury and Barnes-Keoghan, 2007; Allan et al., 2013; Kargel et al., 2014; Molinos et al., 2015; Byrne et al., 2016).

2. Kerguelen geography and climate

The Kerguelen Archipelago is located south of the southern Indian Ocean (48°30'–50°S, 68°27'–70°35'E). Also known as the Desolation Islands, the archipelago comprises 300 islands or so, islets, and reefs. The Kerguelen Islands are ~2000 km away from the coasts of Antarctica, ~3400 km from Reunion Island and ~4800 km from the Australian coast. The archipelago covers 7200 km^2 and has nearly 2800 km of shoreline.

Climate in the Kerguelen is cold oceanic and not polar. Seasons are slightly differentiated but rain is constant. However, precipitation is quite low (850 mm) considering the high frequency (246 days). The mean annual aerial temperature is 5 °C with an annual range of 6 °C. The coldest temperature ever recorded was –9.8 °C during winter 2014. The archipelago is extremely windy. The western coast faces almost continuous winds of an average speed of 35 km.h^{-1}, owing to the island's location in between the Roaring Forties and the Furious Fifties. Wind speeds of 150 km.h^{-1} are common and can even reach 200 km.h^{-1}. Waves up to 12 m–15 m high are also common.

3. Kerguelen hydrology

Isolated in the southern Indian Ocean, the Kerguelen Islands emerge from the Kerguelen-Heard Plateau and stand on the Antarctic circumpolar current. This current provides predictably productive foraging for many species; it is considered a key feature of the Southern Ocean and a primary factor shaping Southern Ocean ecosystems (Tynan, 1998). The archipelago is located in a dynamic oceanographic area positioned at the confluence between several water masses, such as the Antarctic surface water, sub-Antarctic surface water and sub-tropical surface water, near the polar front that is currently shifting southwards (Weimerkirsch et al., 2003). This will likely lead to the coasts being bathed by waters of different temperature, salinity and nutrient contents and will thus impact near-shore ecosystem properties and functioning.

In this framework, the knowledge of the actual position of the polar front is important to accurately estimate the time frame of the phenomena that will affect coastal biodiversity and ecosystem functioning. A 12-year-long satellite observation shows that the mean path of the polar front is asymmetric; its latitudinal position spans from 44 °S to 64 °S along its circumpolar path, reflecting the large spread in latitudinal position (Freeman and Lovenduski, 2016). An up-to-date location of the polar front around the Kerguelen Islands has been defined by Park et al. (2014), corresponding to the 2 °C isotherm (Fig 1). The polar front is a key indicator of circulation, surface concentration of nutrients and biogeography in the Southern Ocean, all of which is necessary for the contextualisation of observations, environments and stands. Its proximity to the Kerguelen islands allows the prediction of significant changes in marine life conditions (Scheffer et al., 2016).

4. The need for a long-term monitoring programme

To be interpreted and for the potential trends to be identified, environmental changes must be

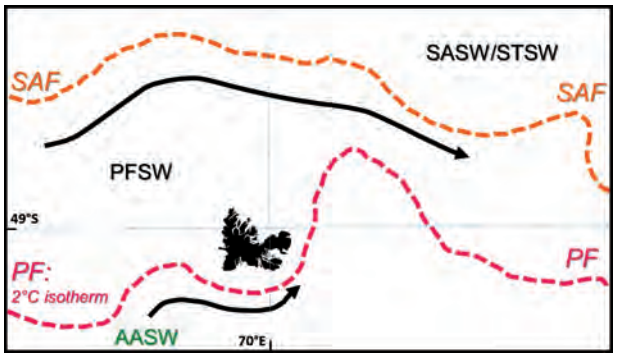

Fig 1: Location of the polar front (PF) and of the sub-Antarctic front (SAF) in the vicinity of the Kerguelen Islands. The Kerguelen Plateau is a major bathymetric barrier to the eastward flowing Antarctic circumpolar current (black arrows). PF marks the boundary between Antarctica cold waters and warmer waters of the polar front area. It is defined as the northernmost extension of the Antarctic winter waters (lower than 2 °C). Expected latitudinal variations of frontal systems (PF and SAF) will create areas of water masses mixtures and/or will get waters of different characteristics (temperature, salinity, nutrients) in contact with the coastal benthos. Redrawn and simplified after Park et al. (2014).

recorded, which requires the establishment of an integrated long-term observing system. This is the aim of the Institut Polaire Français Paul-Émile Victor (IPEV) programme no. 1044 – PROTEKER, which uses a multidisciplinary approach: oceanographic measurements; benthic mapping; and genetic, eco-physiological, isotopic and environmental analyses. In addition to the collection and monitoring of biodiversity, it also aims at providing scientific data to managers of the National Nature Reserve of the French Southern Lands (RNN TAAF) in charge of protection and conservation issues.

Therefore, the mid-term and long-term objectives are to:

- identify, track, attribute and predict ecosystem changes as the basis for vulnerability assessments and adaptive management; and
- provide sentinels of more widespread change in the sub-Antarctic area.

Key research questions include:

- What are the changes occurring in sub-Antarctic near-shore ecosystems that are due to global change?
- What are the drivers of climate change impacts on sub-Antarctic near-shore ecosystems?
- Which species and/or processes are suitable for tracking the effects of environmental change?
- What are the sensitivities of sub-Antarctic benthic biodiversity to environmental stressors? What are the critical thresholds that would give rise to irreversible impacts?

The aim of this article is to present the Kerguelen underwater observatory, the selected monitored sites, their equipment and the very first results.

5. Strategy for the selection of the monitored sites

The most efficient way to explore rocky shores is to dive in order to observe, collect and/or experiment. This technique was used at the Kerguelen Islands for the first time at the beginning of the 1960s. Scuba dives were done in the Morbihan Bay during the austral summer 1962–1963 down to 15 m depth. However, considering the Kerguelen's harsh conditions and even if the sites to study are in the near-shore, a support vessel is needed even if dives are made in sheltered places. From 1970 to 1989 *La Japonaise*, an old converted 14 m long whaleboat moored at Port-aux-Français, was used for short coastal research programmes. However, she was not able to sail outside the Morbihan Bay. It was not until 1990 that it has been possible to work all around the main island and to implement more comprehensive programmes using the 24 m long trawler *La Curieuse*. One of the programmes was dedicated to the sub-Antarctic benthos and studied various issues in depth, including: autecology; synecology; life cycles; developmental biology; population dynamics and genetics; phylogeography; phylogeny; and trophic web. The resulting knowledge served as the main basis for the design of the underwater observatory.

PROTEKER was launched during the austral summer 2011–2012. Several marine laboratories from France, Belgium and Chile have been involved. Eighteen near-shore sites of the main island (Fig 2) have been revisited by divers making observations, photo and video surveys, looking for the best places and ways to install loggers and settlement plots. The vicinity of the sites was explored down to 50 m and 100 m depth using a beam trawl and remotely operated vehicle (ROV) images.

6. Installed equipment

The equipped sites are to be visited yearly, but inclement weather conditions, lack of vessel or crew staff availability, and ineffective scheduling may prevent equipment being recovered. All these conditions suggest that the equipment should have long-term autonomy in addition to high resistance to harsh conditions.

6.1. Temperature loggers

Chosen for this programme was the HOBO® Water Temp Pro v2 Logger with an autonomy of 42 000

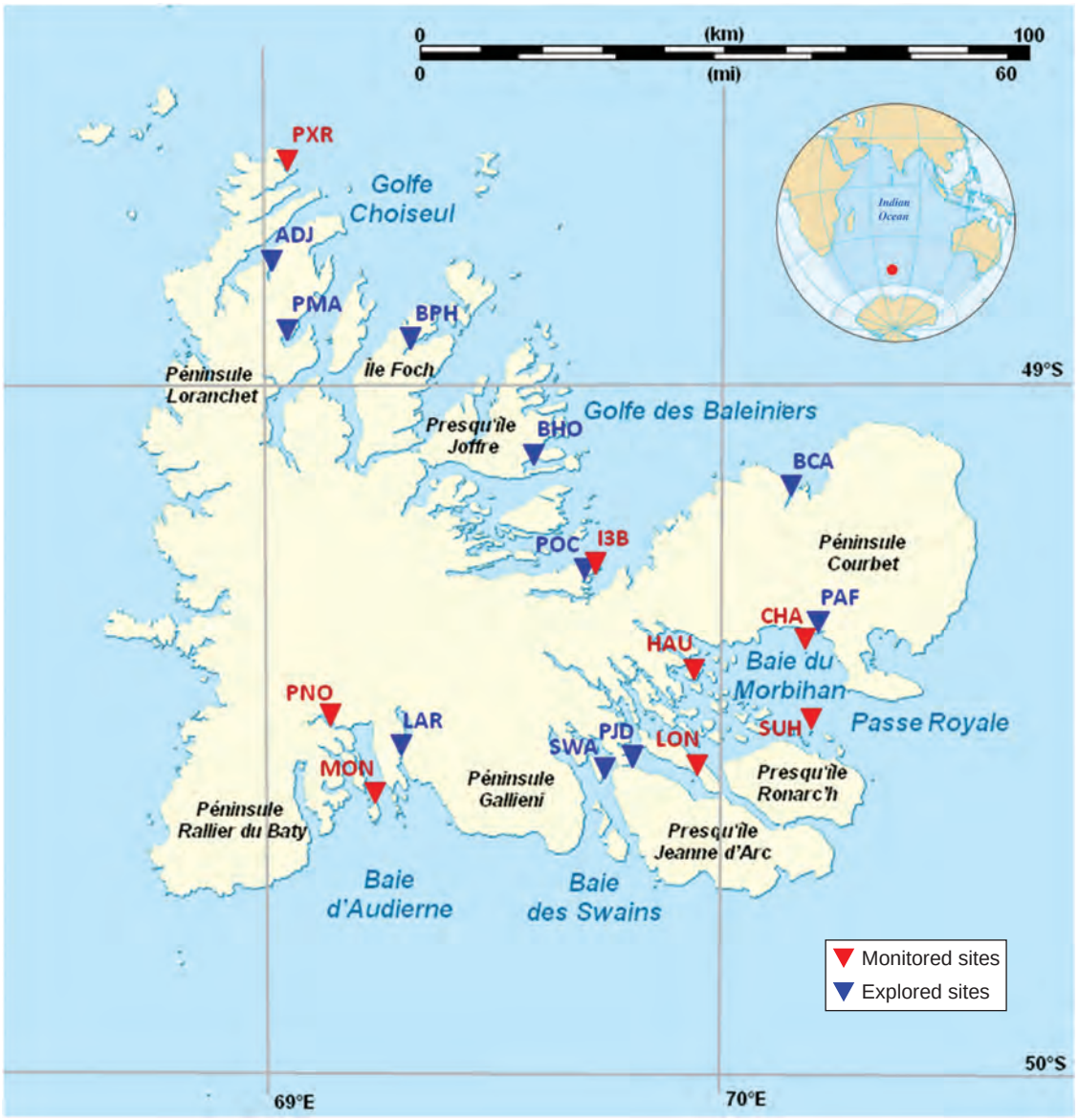

Fig 2: Map of the monitored sites and of the other explored sites in order to validate the representativeness of the selected ones.
Sector Morbihan. PAF: Port aux Français, HAU: Ile Haute, LON: Ile Longue, PJD: Port Jeanne d'Arc, Passe Royale, CHA: Ilot Channer, SUH: Ile Suhm, Swains SWA: Baie des Swains, Audierne LAR: Baie Larose, PNO: Fjord des Portes Noires, MON: Ile du Prince de Monaco, Choiseul PXR: Port Christmas, ADJ: Anse du Jardin, PMA: Port Matha, BPH: Baie Philippe, Baleiniers Baie du Hopehul, I3B: Ilot des Trois Bergers, POC: Port Couvreux, BCA: Baie des Cascades.

measurements that makes a six-year autonomy for one measurement per hour. It is installed in a protective PVC box attached to a threaded rod sealed in the substratum (Fig 3). Precision of sensors as specified by the manufacturer is ±0.2 °C, which is adequate in waters where temperature varies by several degrees a year. The logger is equipped with an optic USB interface for rapid data readout. Drift is estimated to be at 0.1 °C.yr^{-1}.

6.2. Settlement clay plots

Using artificial substrata for comparing the colonisation and growth dynamics of sessile assemblages under changing environmental conditions has proved to be a valuable and handy technique (Sutherland, 1974), including in the Southern Ocean (Stanwell-Smith and Barnes, 1997; Bowden, 2005; Bowden et al., 2006). In the present work, the original association of settlement plots to temperature loggers allows precise monitoring of colonisation processes with regard to temperature variation. Eight 20 cm by 20 cm clay plots are deployed in two rows of four units on a stainless support, which is fixed to the substratum at each monitored site. Each plot is independent and can be collected separately in due course (Fig 4) following an established protocol. Yearly exchange has been, and will continue to be, conducted in order to generate multiple temporal series of the settlement

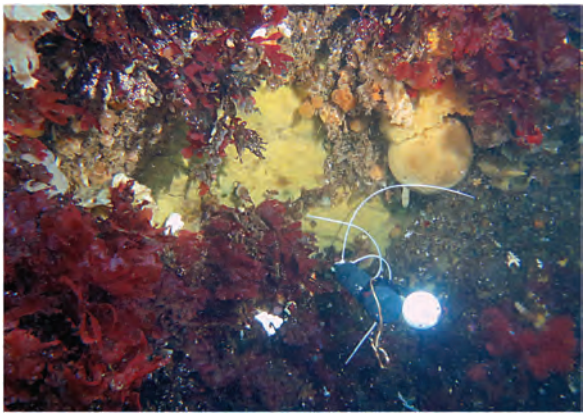

Fig 3: Temperature logger installed at Ile Longue (15 m depth). In order to facilitate the relocation of the logger, a white golf ball is fixed on the bolt to which the thermo-recorder in its protective boot is attached.

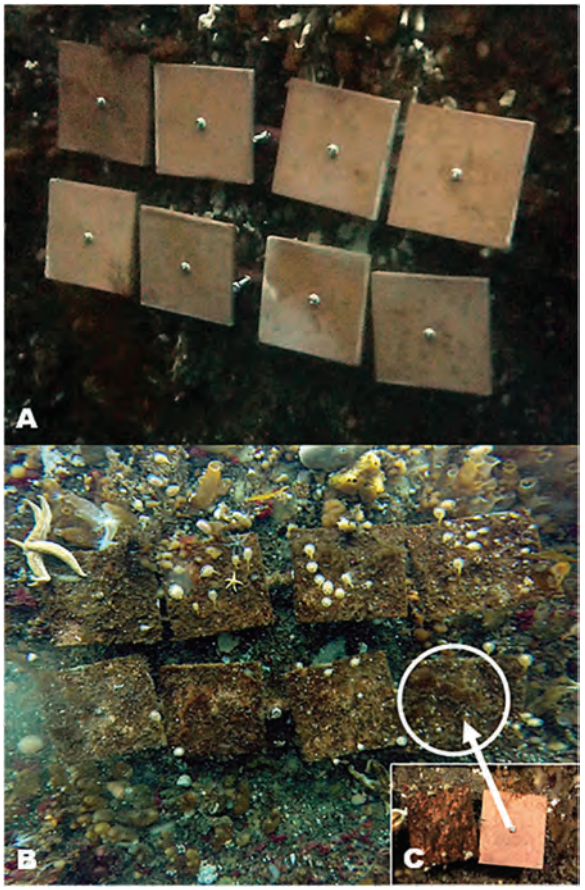

Fig 4: Settlement clay plots, T = 0 (December 2013) and T = 1 year (December 2014) at Ile Suhm. They are immersed and set on rocky walls (A) to study organism settlement over time (B). Each year a tile is recovered. The removed tile is replaced by a new one (C).

dynamics using clay plots (one to eight years). One plot is exchanged after the first year, giving data for a one-year-long settlement period. The exchanged plot and a second 'old' plot are then exchanged after the second year, giving data for a replicate of a one-year-long experiment and for a two-year-long settlement experiment. This process is renewed each year (Fig 5). The datasets obtained will permit evaluation of

1. the different steps of the colonisation process (succession of fouling communities) over an eight-year period, with additional replicates for the first four years (nine replicates of one-year plots, six of two-year plots, three of three-year and two of four-year plots); and
2. spatial and temporal variation of the recruitment process.

When recovered from the sea after one year, the plot is constantly maintained in sea water until it is preserved in 95% ethanol after being photographed overall and close-up, and then is cleaned of the largest fixed organisms, which are preserved separately. Each plot is labelled and safely packaged separately; then it is put in a container and repatriated to the laboratory in mainland France. Biodiversity on each settlement clay plot will be assessed macroscopically and through metabarcoding using DNA based identification and high-throughput DNA sequencing.

7. Results of PROTEKER phase 1

7.1. Monitored sites

The first field campaign was conducted around the Kerguelen Islands on board *La Curieuse* from 12 December 2011 to 9 January 2012. It was dedicated to exploring and selecting the observation sites. Six sites were chosen and one or two temperature loggers were installed at 5 m and 15 m depth.

The second field campaign (30 November to 17 December 2013) made it possible to complete the system with seven monitored sites, north and south of the Kerguelen coast and in the Morbihan Bay. Temperature recorders were deployed as well as settlement clay plots.

The third and last scientific cruise took place during the austral summer 2014, from 18 November to 18 December, and achieved the first phase of the programme: the setting up of the Kerguelen underwater observatory consisting of temperature loggers positioned at 5 m and 15 m depth and clay plots at 10 m depth, at eight sites.

The eight monitoring sites (four in the Morbihan Bay, two along the northern coast and two along the south – see Fig 2 and Table 2) were chosen because they match the requirements of being representative of sub-Antarctic habitats and being in accessibility compliance with the safety standards of scuba diving.

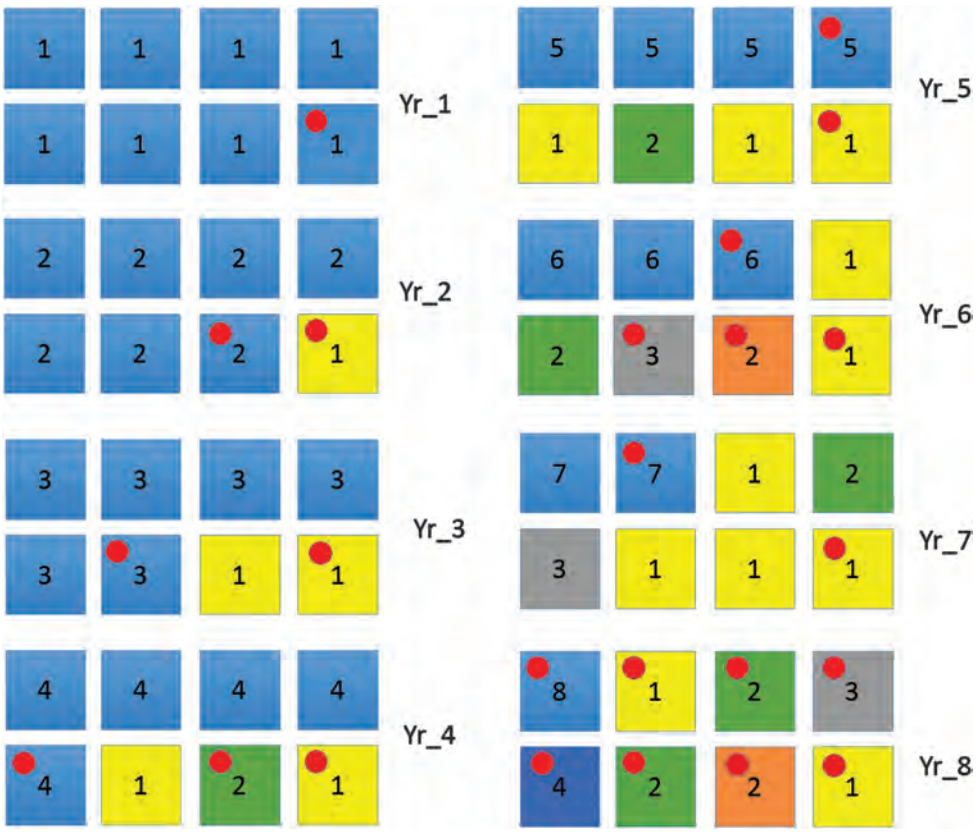

Fig 5: Design of the eight-year-long experiment using clay settlement plots. The initial plots (see Table 2) are in blue. Red dots indicate the exchanged/collected plots that turn to a different colour in subsequent years. The numbers in the plots indicate their age for the different years of the experiment (Yr_1, Yr_2, etc.).

Table 2: Location of monitored sites and dates of installation of temperature loggers and settlement plates.

Sectors	Sites	Latitude South	Longitude East	Depth	1st season	2nd season	3rd season
Passe Royale Royal Sound	Channer	49°22'59"	70°11'08"	5 m			24/11/2014
				15 m			24/11/2014
	Suhm	49°29'36"	70°09'41"	5 m		04/12/2013	
				15 m		04/12/2013	
Baie du Morbihan Morbihan Bay	Haute	49°23'15"	69°56'29"	5 m	22/12/2011		
				15 m	22/12/2011		
	Longue	49°32'19"	69°53'03"	5 m	21/12/2011		
				15 m	21/12/2011		
Audierne	Portes Noires	49°29'39"	69°08'58"	5 m		08/12/2013	
				15 m	01/01/2012		
	Prince de Monaco	49°36'00"	69°14'23"	5 m		07/12/2013	
				15 m	02/01/2012		
Baleiniers	Trois Bergers	49°17'24"	69°42'41"	5 m		01/12/2013	
				15 m	28/12/2011		
Choiseul	*Port Christmas* Christmas Harbour	48°40'55"	69°01'58"	5 m		27/11/2013	
				15 m	26/12/2011		

7.2. Sea water temperature monitoring

Only temperature is currently and continuously measured. Results are posted on <www.proteker.net> and updated after each campaign. Due to time lags between logger installations over three summer campaigns and adverse meteorological conditions, gaps occurred in the temperature monitoring at certain sites. Despite this, from very preliminary and somewhat incomplete results, seasonal variability and site differences were observed. A difference up to 8 °C may occur between summer and winter in the Morbihan Bay at 5 m depth and up to 7 °C at 15 m depth. These differences are smaller outside the bay, being from 3 °C to 6 °C at both depths. The maximum values recorded in the Morbihan Bay are 8.9 °C at 5 m and 8.2 °C at 15 m (Ile Longue).

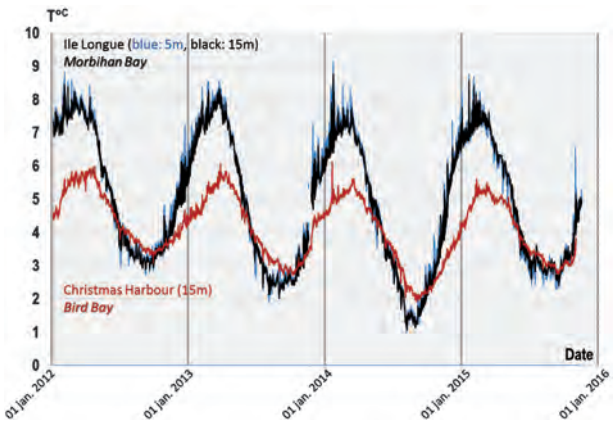

Fig 6: Temperature monitoring of sea water at sites in the Morbihan Bay (Ile Longue) and outside (Bird Bay/Christmas Harbour) from 6 January 2012 to 9 December 2015.

They were 7.2 °C at 5 m and 7.0 °C at 15 m for the Ilot Channer. Concerning the minimum values, they were 1.1 °C (5 m) and 1.2 °C (15 m) for Ile Longue and 1.4 °C (5 m) and 1.5 °C (15 m) for Ile Suhm.

Along with a seasonal cycle, it was also observed that the sites outside the Morbihan Bay were the coldest overall, with respect to the maximum values. The lowest ones are all similar either in or out of the bay. During three successive winter seasons (2012–2014) minimum temperature decreased by 1 °C each year (3 °C to 1 °C) and increased to 2.5 °C in winter 2015. Fig 6 gives a comparative example (of depths and sites) of the most complete records.

In Fig 6, sea water temperature shows a regular seasonal cycle. The maximum temperatures are quite constant over the observed years, while the minimum ones show variations of more than 1 °C between successive years. The maximums are higher at Ile Longue (8.6 ± 0.2 °C) than at Christmas Harbour (5.7 ± 0.2 °C). The minimum average is 2.1 ± 0.7 °C at Ile Longue and 2.7 ± 0.5 °C at Christmas Harbour.

7.3. Colonisation dynamics monitoring

The colonisation dynamics will be estimated from the colonised clay plots recovered each year (metagenomics analysis).

8. Next step

The programme has just been renewed for four more years (2015–2018) to achieve, complement and widen the monitoring programme, and be able to analyse ecological responses of coastal marine biodiversity to climate change. The second step of the programme will consist of (1) complementing the monitoring of the equipped sites (equipment changing, observations and samplings associated to settlement plots) and recording supplementary water parameters (pH, salinity, oxygen, turbidity); (2) benthic habitat mapping (using diving, towed gears, and ROV) to analyse mature assemblages where settlement plots were set up and according to depth, and (3) reinforcing the phylogeographic, trophic and ecological analyses performed on target taxa. Practically, the next step of the programme aims to:

- achieve metagenomics analyses;
- complete the network of equipped stations at relevant sites;
- update species inventories (using diving, towed gears, and ROV) in the vicinity of these sites;
- publish illustrated field guides (photos, video) and a database (indexing and cataloguing data, making them interoperable, traceable and compatible with international systems, as well as contextualising and illustrating them);
- set up new sensors (pH, salinity, oxygen, turbidity) based on the installation of a durable energy source (land-based photovoltaic/wind hybrid system);
- estimate speed and quality of colonisation/recruitment (settlement plots);
- choose model species with large distribution area or endemic (population genetics, phylogeography studies) to estimate connectivity or the existence of self-recruitment;
- contribute to the necessary scientific bases for a management plan of the coastal marine domain in the RNN TAAF; and
- train members of the RNN TAAF staff so they are capable of ensuring the long-term monitoring at the selected sites.

Meeting all the aforementioned objectives requires having dedicated and relevant means available for work at sea. In particular, it would require an appropriate vessel to access the sites located outside the Morbihan Bay from which specific gear and activities (ROV, beam trawls and diving) can be operated. Results are expected to allow the production of distribution and sensitivity models for the coastal marine biodiversity of the Kerguelen Islands with regard to the expected environmental changes. The whole system will bring conservation managers the scientific grounds for determining how coastal zones should be protected and managed. PROTEKER makes up part of a larger observatory network in the Southern Ocean: it has joined the French Institut Écologie et Environement (INEE) Antarctic and sub-Antarctic workshop area (ZATA) and the Scientific Committee on Antarctic Research (SCAR) International Action Groups – the Antarctic Nearshore and Terrestrial Observing System (ANTOS) and the Integrated Science for the Sub-Antarctic (ISSA).

Acknowledgments

This research was supported by IPEV (programme no. 1044) and by the IMBE team for management of biodiversity and natural habitats. We are indebted to the RNN TAAF for completing our team in the field with a scientific diver and making the semi-rigid ship *Le Commerson* (R Vergé, skipper) available in the Morbihan Bay. We thank the operational teams of the IPEV and of the TAAF for the logistics on the base of Port-aux-Français and on board the RV *Marion-Dufresne II*. We are particularly grateful to the captains and the crews of the three scientific cruises of *La Curieuse* (B Aspa (chief engineer) [1], V Benard (mechanic trainee) [3], M Cadet (mechanic trainee) [2], B Caffier (cook/deckhand) [1, 2, 3], L Conillen (first mate) [1], A Daujat (captain) [1], C Hemmer (2nd engineer) [3], S Laffont (deckhand) [3], PY Le Bren (chief engineer) [2], A Michelot (chief engineer) [3], Y Mucherie (captain) [2, 3], J Payet (deckhand) [1], X Payet (deckhand) [2], Y Rivière (mechanic trainee) [1], A Sautron (2nd engineer) [1, 2], P Samuel (first mate) [3], L Seguinneau (first mate) [2]. Posting of the temperature monitoring in the form of interactive graphics was possible thanks to R David, who installed the open source JavaScript charting library "*dygraphs*" on the PROTEKER website.

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doi:10.3723/ut.34.011 Underwater Technology, Vol. 34, No. 1, pp. 11–20, 2016 www.sut.org

Society for Underwater Technology

Technical Paper

An optimised method for scuba digital photography surveys of infralittoral benthic habitats: a case study from the SW Black Sea Cystoseira-dominated macroalgal communities

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Received 8 August 2016; Accepted 11 October 2016

Abstract

An improved digital photogrammetry scuba survey method, using high resolution camera (14.7 mp, 60/90 cm, 0.63 m^2 image size, 2321.5 pixels per cm^2) was developed and tested in studies of the structure and distribution of infralittoral macroalgal communities in the SW Black Sea. Results obtained from cover estimation based on the point intercept method were compared and validated against contour outline estimation, determining the optimal number of sampling points necessary for reliable and repeatable results (100 points per image, 158 points per m^2). Comparison of results on macroalgal community structure obtained from photo sampling and transect destructive sampling showed very similar results, confirming the photo method as a reliable approach. The application of high resolution digital cameras and semi-automated software packages for cover estimation of benthic species (CoralPointCount Extension) made this method significantly more effective and less time-consuming – both underwater and during the sample processing – than classical transect destructive sampling methods. The developed method was applied in experimental studies of changes in structure of macroalgal communities in an eutrophication gradient, as well as in the mapping of Zostera seagrass and Cystoseira macroalgal communities.

Keywords: digital photography, photogrammetry, benthic surveys, Cystoseira, Black Sea

1. Introduction

1.1. Benthic ecology photography methods

One of the main methodological challenges in studying benthic marine ecosystems is getting direct access to the objects of study (Underwood et al., 2000). Owing to the inaccessibility of the ocean floor to humans, a majority of the pioneering studies of the benthos have been carried out using sampling and measurements with instruments deployed from ships, which have not given a clear picture of the overall structure and dynamics of these ecosystems (Solan, 2003).

The development of scuba diving technology, reliable underwater photography and videography instruments in the 1950s and the 1960s revolutionised shallow-water marine biological research by giving researchers direct access to the benthic ecosystems. The usage of photography as a research tool in benthic ecology was further improved by the adaptation of photogrammetry methods for measurements of sizes of objects (Ray, 1999), as well as by the application of formal experimental designs and sampling procedures in filming the benthos and the quantitative analysis of the collected photos and videos (Dethier et al., 1993; Underwood et al., 2000; Ryan, 2004; Leujak and Ormond, 2007; Van Rein et al., 2011).

Some of the first photogrammetry studies of hard bottom zoo- and phytobenthic communities were those of Lundalv, who developed a stereo photography scuba method for quantitative studies of benthic communities (Lundalv, 1971, 1974). Lundalv et al. (1986) also used it for a long-term study of the changes in the structure of phytobenthic communities along the Atlantic coast of Sweden. Photogrammetry methods were later used extensively in various scuba studies of tropical coral reefs (Whorff and Griffing, 1992; Carleton and

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Done, 1995) and temperate seas littoral communities (Ballesteros, 1992; Kolser et al., 1996; Norris, 1997; Van Rein et al., 2011; Norderhaug et al., 2015). Underwater photography as a tool for documenting species in their natural environment has been used in surveys of the benthos of the Black Sea since the 1960s (Kalugina-Gutnik, 1975; Marinov, 1990; Todorova et al., 2009). Recently, digital photogrammetry and video filming were tested as methods for mapping phytobenthic communities in the NW Black Sea (Minicheva et al., 2014).

1.2. Digital photogrammetry methods

The advent of digital photography in recent years has dramatically stimulated the development of new methods for underwater scientific photography. Its main advantage over classical photography is the practically unlimited number of photos that a diver can take during the time they spend working underwater. This also gives the method a significant advantage over classical destructive benthic sampling, where the number of samples that can be taken is also limited by the time available underwater.

The application of digital photography in benthic ecology research is further aided by software for improvement of image quality of digital photographs (e.g. Adobe Photoshop); for quantitative measurements, e.g. NIJ ImageJ (Schneider et al., 2012); cover estimation, e.g. Coral Point Count with Excel extensions (CPCe) (Kohler and Gill, 2006); PhotoQuad (Trygonis and Sini, 2012); and georeferencing and integration of results in databases (Geospatial expert). Software algorithms for semi-automated and completely automated machine learning image analysis are being currently developed (Purser et al., 2009; Beuchel et al., 2010) and will further improve the effectiveness and usability of digital photography as a tool for benthic ecology studies.

Owing to their effectiveness, digital photography survey methods are finding their place in algological research. Preskitt et al. (2004) developed a rapid method for photogrammetry surveys of macroalgal communities, where photos were taken by scuba divers with a digital camera mounted on a portable and easy to carry PVC frame. The analysis of coverage of species within each photo was done manually using a specially designed software product applying the point intercept method. Results were later integrated in GIS databases.

The developed methodology was widely applied in studies of the spatial structure of phytobenthic communities in Hawaii (Vroom et al., 2006; Vroom and Timmers, 2009). Roelfesema and Phinn (2009, 2010) adapted digital photogrammetry methods for usage in tropical coral reefs and seagrass ecosystems by integrating a system for GPS georeferencing of the photos. They used CPCe (Kohler and Gill, 2006) for manual cover estimation. Georeferenced data were then used for in-situ verification of satellite and aerial photography imagery. Recently, the same authors applied semi-automated methods for image analysis and autonomous underwater vehicle (AUV) based photo surveys that further improved the effectiveness of the methodology (Roelfsema et al., 2013, 2015).

A major challenge in photographic surveys of benthic communities is using effective methods to analyse the presence of visible benthic species and estimate the proportion of area of the substrate covered by them. Traditionally, when using film-based photography and photogrammetry, researchers manually outline the contours of present species and estimate the cover by measuring the dimensions of these contours manually or with image processing software (Ballesteros, 1992; Whorff and Griffing, 1992). This method gives the most precise estimation of the relative abundance of species in a photo sample, but is time-consuming and ineffective when analysing large quantities of images from digital photography surveys.

A more efficient approach for estimating the proportion of area covered by organisms is to calculate the proportion of points intersecting the substrate or organism – the so-called point intercept method (Pielou, 1974). Different point intercept distribution methods can be designed depending on the dimensions of the photo samples and transects, on the needed precision of estimation, and on the available time and resources for the image analysis. Of these methods, the stratified-random point sampling provides the most consistent and precise results (Ryan, 2004). Current software packages for image analysis (such as CPCe) allow the application of both the contour outline technique and the point intercept method, allowing the option for different point distribution designs (Kohler and Gill, 2006).

1.3. Purpose of study

In recent decades of anthropogenic eutrophication, pollution, marine resources exploitation and climate change, pelagic and benthic ecosystems in the Black Sea have undergone severe changes in their distribution and structure (Daskalov et al., 2007; Mee, 1992; Oguz and Gilbert, 2007; Zaitsev, 1992). The period of increased eutrophication in the 1980s and the 1990s severely changed the spatial distribution and species composition of macroalgal communities, especially in its western section (Milchakova and Petrov, 2003; Minicheva et al., 2008; Berov et al., 2012). The recent implementation of

EU marine environmental legislation in Bulgaria pushed the need for developing standardised and efficient methods for rapid assessment of the spatial distribution, community structure and ecological status of coastal habitats. Such legislation comprises the Habitats Directive (Council of the European Communities, 1992), the Water Framework Directive (Council of the European Communities, 2000) and the Marine Strategy Framework Directive (European Parliament, Council of the European Union, 2008).

The purpose of this study is to improve on already available methods for digital photogrammetry surveys of phytobenthic communities and to adapt them to the specific conditions of the Black Sea. The ability of the selected method to reliably detect the community structure of typical Black Sea upper infralittoral macroalgal communities is also evaluated, by comparing it with results obtained by classical destructive sampling methods. The precision and effectiveness of different methods for cover estimation is also assessed.

2. Materials and methods

2.1. Photo system

The underwater photo system used in this study is based on an improved version of the original system developed by Preskitt et al. (2004). It employs a Canon G10 14.7 megapixel camera placed in an Ikelite waterproof housing with a depth rating of 60 m. The system is equipped with a wide-angle converter Ikelite WD-4, correcting for the optical effects of water and giving a 28 mm angle of coverage without any noticeable image distortion. An Ikelite DS-160 underwater strobe (205 lumens) is also used, providing sufficient illumination for the light conditions in the infralittoral of the Black Sea coastal zone.

The photo system is mounted on a tetrapod PVC frame built of 7 mm diameter pipes, as designed by Preskitt et al. (2004) (Fig 1). The PVC pipes are very robust and resistant to corrosion. When filled with water, they have slightly negative buoyancy, making them easier to operate and carry underwater than a metal frame with the same dimensions. The legs are mounted on a rectangular frame, which ensures that the photo system has as many points of contact with the terrain as possible, even on uneven rough rocky bottoms terrain. Thus the camera can always be positioned parallel to the plane of the photographed objects and at equal distances from all points within the filmed area.

The distance between the camera and the ground is 96 cm, giving a 60 cm × 90 cm and 0.632 m^2 size of each photo sample, resulting in a resolution of 2321.5 pixels per cm^2 of the image. This is a significant improvement in image size and resolution compared to the original design of Preskitt et al. (2004), which takes photos with a size of 0.16 cm^2 with much lower image resolution (1747.6 pixels per cm^2). The selected photo sample size and obtained image resolution are appropriate to identify and measure the size of the typical Black Sea infralittoral macroalgal species, which vary in size between the ranges of 1 cm–10 cm (e.g. the red macroalgae *Ceramium virgatum, Callithamnion corymbosum, Gelidium spinosum, Phyllophora crispa*, the green *Cladophora coelothrix, Ulva intestinalis*) and 20 cm–60 cm (for the dominant brown macroalgae *Cystoseira barbata, Cystoseira bosphorica*, and typical green macroalgae such as *Ulva rigida, Cladophora sericea, Chaetomorpha linum*, as well as the angiosperms *Zostera marina* and *Zostera noltei*).

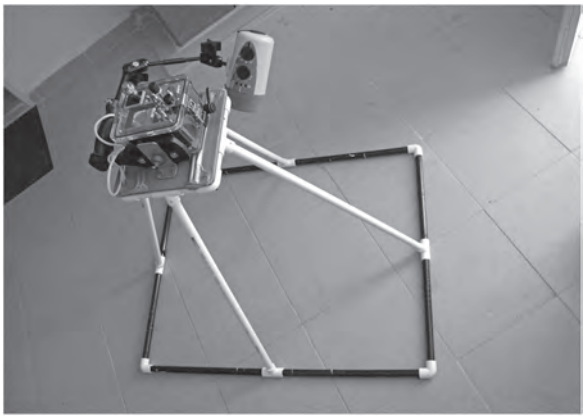

Fig 1: Overall view of the photo system used in this study.

2.2. Application of the system underwater

When using the photo system in surveys underwater, the system is positioned over the selected sampling area by a scuba diver. The camera is used in 'aperture priority' mode, with a maximum possible aperture opening, thus ensuring the deepest possible focal depth at shutter speeds greater than 1/60. In areas where light conditions are variable and little time for camera programming is available, the 'Program' mode of shooting of Canon G10 also provided good image quality. At depths below 3 m–4 m, where less light is usually available in the turbid coastal waters of the Black Sea, the Ikelite DS-160 strobe is also used. Using two strobes would provide even better illumination, but would make the system bulkier and harder for scuba divers to use.

The photo surveys of upper-infralittoral macroalgal communities in the study area were usually carried out by a team of two divers. At each sampling location, a 10 m transect line was positioned on a flat rocky substrate at depths between 2 m and 3 m, which is the optimal depth range for growth

and development of Cystoseira-dominated communities in the Black Sea (Kalugina-Gutnik, 1975). The camera system was placed on top of the transect line, with the wide axis of the frame aligned perpendicularly to the transect. A series of photos adjacent to each other covering the whole length of the transect were taken, resulting in a total of 16.6 images for each 10 m. Only images with good quality were used in the analysis of coverage, resulting in 10–17 images per transect, depending on water turbidity and mobility of the macroalgae resulting from wave action.

In order to be able to better identify the macroalgal species that were photographed along the transects, three randomly distributed destructive samples (20 cm/20 cm) were collected along the same transect line using the transect sampling method (Gambi and Dappioano, 2004). Each sampling frame was placed at a preselected random location on top of the transect line and was photographed before collecting plant material.

Four seasonal surveys were carried out (July and September 2009, and June and September 2010) at seven sampling locations along the Southern coast of the Burgas Bay (see Berov et al., 2012; Berov, 2013 for detailed description of sampling sites). A total of 23 upper-infralittoral transects were completed, along which 83 destructive samples and 257 photos with sufficient quality for analysis were taken. Several transects were skipped during certain surveys due to bad weather, diver safety issues and technical problems. The two sampling strategies were compared based on the number of samples and photos taken per dive, the time needed for sample and photo analysis, the area of the benthos sampled, and the number of species identified per sample and for the whole survey.

2.3. Selection of optimal method for cover estimation

Results obtained from contour outline estimation of cover were compared with those from random stratified point intercept estimations with different number of points. For purpose of this evaluation, a single test photo of a typical upper infralittoral Cystoseira-dominated macroalgal community was selected. The photo included the typical big macroalgal species: individual whole plants of *Cystoseira bosphorica* and *Ulva rigida* (20 cm–60 cm), smaller patches of Cladophora spp. and the blue mussel *Mytilus galloprovincialis* (10 cm–20 cm), as well as small individual macroalgae *Callithamnion corymbosum* (1 cm–10 cm).

The percentage coverage of these organisms in the selected test image was measured using the 'area-length analysis' tool in CPCe v. 3.6. The results from this measurement were compared with random stratified point intercept evaluation with 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 and 130 intercept points on the same image using the 'point overlay' tool in CPCe 3.6. In order to check the repeatability and reliability of the obtained results, the analysis with 60, 70, 80, 90, 100 and 130 points was repeated six times by the same operator. The average time needed for each of the measurements was also recorded.

The results obtained from these two analyses were compared using a root-mean-square error (RMSE) of the percentage difference between the results from two measurements (Ryan, 2004). The standard deviation of the percentage coverage for each species and number of point intercepts were also compared. In order to explore the variability in results obtained with different numbers of points and their similarity to the 'referent' results obtained with contour outline, a Bray-Curtis similarity analysis of all replicates and estimations was done, and visualised as a multidimensional scaling (MDS) plot, using Primer 6 (Clarke, 1993; Clarke and Warwick, 2001; Anderson et al., 2008). The main criteria for selecting the most appropriate method were that it allows reliable and replicable detection of the presence and quantities of both large and small patches of visible benthic organisms, provides replicable cover estimates and community structure data, and is time effective.

2.4. Image analysis procedure and comparison with destructive sampling

The selected approach for point-intercept cover estimation was later used in the analysis of images from the upper infralittoral transects sampling that were combined with destructive sampling. Destructive samples were processed following standard algological methods – identification of specimens to species level and measurements of their horizontal projected cover (see Berov et al., 2012 for details). Photo samples were analysed using the 'point overlay' tool in CPCe 3.6. Organisms located at each of the intercept points were identified based on visible species or genus specific morphological features and sizes, as well as by comparison with the plant material collected along the same transects.

Species-level identification was possible for many of the dominant macroalgae, including the brown *Cystoseira bosphorica*, *C. barbata*, *Zanardinia typus*, the green *Ulva rigida*, the red *Polysiphonia elongata*, *P. subulifera*, *Ceramium virgatum*, as well as zoobenthic species such as the bivalves *Mytilus galloprovincialis*, *Mytilaster lineatus*, and the whack snail *Rhapana venosa*. Members of the genera with similar morphology,

such as those from the genera Cladophora (with the species *Cladophora sericea, C. albida and C. vagabunda*), Gelidium (*Gelidium spinosum* and *G. crinale*), Ceramium (*Ceramium virgatum, C. tenuicorne, C. pedicellatum*) Ulva (*Ulva linza, U. intestinalis, U. prolifera*), Chaetomorpha (with *Chaetomorpha aerea* and *C. linum*) could not be distinguished from each other, and were thus identified to genus level. An image reference library with photos of typical zoo- and phytobenthic species for the study area was created.

In order to evaluate the similarity of community structure estimates from the photo transect and destructive sampling, results from sampling of *Cystoseira bosphorica*-dominated communities were compared using similarity percentage (SIMPER) analysis in Primer 6 (Anderson, 2001). Photo samples and destructive samples from the June 2010 survey were used, as this was the season with the greatest biodiversity and quantities of macroalgae detected in the study.

3. Results

3.1. Comparison of cover estimation methods

The comparison of cover estimation results obtained with different number of random stratified points and the contour outline cover method demonstrated a gradual increase in the precision and repeatability of the obtained results with increasing number of sampling points. When using 90 and more sampling points, the standard deviation between the two methods was below 2.5%, both for the large and small patches of benthic species. The RMSE estimation of variability of results between the two sampling strategies also showed a gradual increase in accuracy and repeatability with increasing sampling points (Table 1). The RMSE for both dominant big species (*Cystoseira bosphorica*) and small and rare species (*Callithamnion corymbosum*) with 100 sampling points was lower than 4.00 and slightly increased when using 130 sampling points. In the latter case, an overestimation of the cover of rare and small categories was observed (Table 1).

Cover estimations using fewer than 60 sampling points (not shown) were very variable and, in most cases, did not detect the presence of the smaller species categories. The MDS plot of the Bray-Curtis similarity matrix of the random-stratified sampling point's replicates of the test photo also showed a clear tendency of obtaining more precise and less variable results with increasing number sampling points (Fig 2). Estimations with 90 points had 94% similarity with the referent contour outline cover estimation, while those with 100 points had 98.6% similarity. Measurements with 130 points were less similar to the referent results (95.06% similarity), as they overestimated the presence of small and rare species.

The comparison of the time necessary to perform the different cover estimation procedures clearly shows that the point intercept method is significantly more efficient (Table 2). An experienced user, who is familiar with the dominant benthic species, takes between 4 and 7 min to analyse an image when using 100–130 points for estimation of cover, compared to 30–60 min if using the contour outline technique. Both of these methods of cover estimation are still faster than the time it takes an

Table 1: Percentage mean cover of benthic organisms in test photo and standard, and RMSE estimates between percentage coverage of different species in test photo, estimated with random-stratified point intercept with 60, 70, 80, 90, 100 and 130 points, and contour outline method. Each estimate for different number of sampling points is based on six replicates.

Species	**60 p.**			**70 p.**			**80 p.**			**Contour outline**
	Mean cover	St. dev.	RMSE	Mean cover	St. dev.	RMSE	Mean cover	St. dev.	RMSE	Cover
C. bosphorica	74.52	2.42	10.98	77.40	2.15	8.12	76.48	2.72	7.90	85.28
Cladophora spp.	2.61	1.48	2.89	0.75	0.82	1.02	1.32	0.82	1.46	0.06
U. rigida	17.37	2.73	5.88	14.91	2.14	3.47	15.49	1.57	3.73	12.05
Callithamnion sp.	2.02	1.30	2.02	2.48	1.51	2.51	2.20	1.35	2.19	0.38
M. galloprovincialis	3.50	2.22	2.39	4.48	0.90	2.39	3.52	1.31	1.76	2.23
Species	**90 p.**			**100 p.**			**130 p.**			
	Mean cover	St. dev.	RMSE	Mean cover	St. dev.	RMSE	Mean cover	St. dev.	RMSE	
C. bosphorica	77.19	0.60	8.10	81.82	1.65	3.77	77.73	2.81	4.38	–
Cladophora spp.	1.55	0.58	1.58	0.67	0.81	0.58	0.69	0.34	0.54	–
U. rigida	14.83	2.02	3.33	13.87	2.58	1.73	15.62	3.39	3.06	–
Callithamnion sp.	1.56	0.60	1.30	1.46	0.55	0.95	2.20	0.68	1.70	–
M. galloprovincialis	4.87	1.13	2.83	2.78	1.50	1.48	2.74	0.84	0.60	–

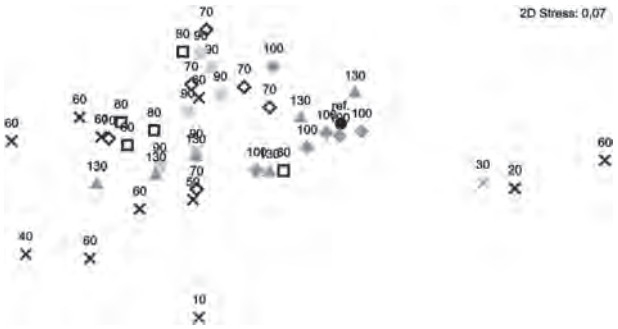

Fig 2: MDS ordination of the Bray-Curtis similarity matrix of percentage coverage of different species in test photo, estimated with random stratified intercept and contour outline methods. Each point represents a cover estimate replicate with different number of points (numbers next to labels). Reference marks the cover estimation based on the contour outline method of the test photo.

Table 2: Time needed for analysis of photos using different number of measuring points (10–130), the contour outline method and processing of a standard macroalgal sample.

Method	Time
10 points	>1 min
20 points	>1 min
30 points	1–2 min
40 points	1–2 min
50 points	2–3 min
60 points	2–3 min
70 points	3–4 min
80 points	3–4 min
90 points	4–5 min
100 points	4–5 min
130 points	6–7 min
Contour outline	30–60 min
Destructive sample processing	30–240 min

experienced algologist to process a standard destructive sample, identify macroalgal species and measure their projected cover (30–240 min).

In addition to the faster sampling processing time, the photo transect method allowed the scuba divers to collect significantly more samples in the limited time underwater. It also permits divers to describe quantitatively a larger area of the studied benthic communities, while detecting a similar number of species as with the quadrant samples (Table 3). As the photo sampling method fails to detect microscopic and rare species, the total number of macroalgae found within the study transects in the quadrant samples was much larger. Nevertheless, the method manages to estimate accurately the cover of the habitat forming macroalgal species - *C. bosphorica* and *C. barbata*. It also gives reliable estimates of the quantities of smaller species that are important indicators of changes in the ecological state of these ecosystems caused by the effects from eutrophication pressures, such as green macroalgae from the genera Cladophora and Ulva, as well as red epiphytic macroalgae from the genera Ceramium, Polysiphonia and Acrochaetium (Berov et al., 2012).

As a result of this analysis, the usage of 100 stratified-random points was selected as the most reliable and efficient approach, which corresponds to ~1 point each 0.006 m^2 of the image, or 158 points per m^2.

3.2. Sampling approaches comparison of photos versus samples

The comparison of the contribution of different species identified and quantified in destructive and photo samples taken within the same sampling transects in Cystoseira bosphorica-dominated community in the study area is shown in Table 4. The photo sampling method managed to detect all dominant species that determine the identity of the studied community found in the destructive sampling. These included the canopy-forming *Cystoseira barbata* and *C. bosphorica*, the epiphytes from the genus Ceramium, as well as the basiphytic *Ulva rigida*. The photo sampling method overestimated the contribution of epiphytic species (e.g. Ceramium spp. 3.19% in destructive samples, 11.43% in photo samples), and underestimated the contribution of basiphytic species, which grow partially hidden below the canopy.

Due to the higher number of photos collected along the sample transect, the analysis of the images reviewed the presence of species that were not found in the destructive samples. These include the canopy forming *Cystoseira barbata* – which usually grows in more sheltered locations but occasionally occurs in exposed *C. bosphorica*-dominated areas – and the ephemeral red *Callithamnion corymbosum*. The overall number of species found in destructive samples in all surveys is significantly higher than those found in photo samples (63 and 11, see Table 3).

4. Discussion

The developed and tested digital photography point intercept method for estimating cover proved to be reliable and efficient in studies of the community structure of infralittoral macroalgal communities in the Black Sea. The fast and efficient collection of data by scuba divers makes it suitable for in-situ experimental studies of benthic communities.

A major problem during the survey campaigns was the bad quality of photos taken in areas with low water transparency and high turbidity. This was especially problematic in the more eutrophicated

Table 3: Comparison of effectiveness of destructive sampling (20/20 cm) and photo transect sampling (100 points random-stratified analysis) based on results from 2009–2010 upper infralittoral survey. (See Berov et al., 2012 and Berov, 2013 for a detailed description of survey methods.)

Activity/sampling method	Quadrat samples	Photo transect
Samples per dive	6–12 samples	40–50 photos
Time per sample	5–10 min	<1 min
Time to analyse sample	30–240 min	4–5 min
Area sampled per dive	0.24–0.48 m^2	20 m^2–30 m^2
Species identified per sample	3–15	3–11
Total number of species found	63	11

Table 4: Comparison of results of SIMPER analysis percentage contribution of species identified from destructive sampling and corresponding species or genus identified from photo transect sampling. Samples and photos were taken along the same transect lines in the upper infralittoral zone at Cystoseira bosphorica-dominated sampling stations in June 2010. Species marked with n/a in the photo transect column were not identified in the photo samples and vice versa. Analysis based on 17 destructive samples and 44 photo samples.

SIMPER destructive sampling		SIMPER photo transect	
Species	**contrib. %**	**Species**	**contrib. %**
Cystoseira bosphorica	93.75	*Cystoseira bosphorica*	67.12
*Ceramium strictum***	2.18	Ceramium spp.**	11.43
*Ceramium diaphanum***	1.01		
*Ceramium virgatum**	0.28		
*Ulva rigida**	0.97	*Ulva rigida**	5.25
*Cladophora sericea***	0.64	Cladophora spp.**	3.49
*Acrochaetium cruciatum***	0.3	n/a	–
n/a	–	*Callithamnion corymbosum***	0.75
n/a	–	*Cystoseira barbata*	11.5

* basiphytic species
** epiphytic species

inner Burgas Bay, where low water transparency and high concentrations of suspended particular matter was frequent in the summer months and resulted in 30%–40% loss of photos. At these survey stations the increased productivity of phytoplankton, caused by elevated nutrient concentration, resulted in high Chlorophyll-a concentrations (3.36 $\mu g.l^{-1}$, average for 2009–2010, see Berov et al. (2012)) and light attenuation coefficients (Kd = –0.48, average for 2009–2010) and low water transparency (3.81 m Secchi depth, average for 2009–2010). The low levels of illumination at depths below 2 m to 3 m were partially compensated by the use of the strobe. However, this also proved problematic when the amounts of suspended matter were high and caused backscatter problems.

Photo surveys in the study stations with good overall water quality in the outer Burgas Bay had a much higher percentage of photos with sufficient quality (e.g. Cape Maslen Nos area, with average for 2009–2010 [Chlorophyll-a] = 2.02 $\mu g.l^{-1}$, [seston] = 1.17 $\mu g.l^{-1}$, 7.14 m Secchi disk depth and Kd = –0.265, see Berov et. al (2012)). At these more exposed coastal areas, a major challenge was the movement of stems of macroalgae due to wave action. This resulted in blurry photos, which could not be used for species identification. Survey results in these exposed areas were good only if taken during days with little or no wave action, which could prove problematic in seasons with more frequent storms.

Another major challenge in using photo survey techniques for macroalgal community studies is the inability to detect the presence of conspicuous species living in the canopy of the habitat-forming species or on the substrate below them (Preskitt et al., 2004; Van Rein et al., 2011). This proved to be a problem in this survey as well, as some of the basi- and epiphytic algae and zoobenthic species that are typical for the Black Sea Cystoseira-dominated communities could not be detected in the photos. This resulted in an overall smaller number of species found in the photo surveys compared with the results from the destructive sampling. Additionally, many of the detected green and red macroalgae (genera Cladophora, Ulva, Ceramium,

Polysiphonia) could not be identified to species level, as that requires an actual sample to be studied under a microscope. In cases where the main task of an infralittoral benthic survey is the evaluation of the overall biodiversity of plant communities, photo techniques should only be used as a complementary tool. Nevertheless, because of the relatively low overall biodiversity of the macroalgal flora of the Black Sea, in most cases a similar number of species was detected in the photo surveys as in the samples studied in the laboratory (see Table 3).

The comparison of cover estimations from photos with data from samples from the same transects showed an interesting effect of overestimation of the contribution of epiphytic species growing on top of the canopy-forming macroalgae to the overall community structure (Table 4). On the other hand, the reduction of the complex three-dimensional structure of the habitat-forming Cystoseira plants to a two-dimensional image projection resulted in an underestimation of their actual quantities and contribution to the community structure. These effects should be taken into account when analysing results from such studies, in cases where a more 'objective' estimation of the quantities of benthic organisms is needed. For example, for estimates of biomass and productivity, photo sampling needs to be combined with actual sample collection.

4.1. Examples of method usage

The method has already been applied with good results in a study of the change in infralittoral macroalgal communities in an eutrophication gradient (Berov, 2013). It has also been used as a tool for the evaluation of the ecological quality of coastal water bodies following the guidelines of the EU Water Framework Directive (Berov et al., 2013). Using the photo system in combination with the GPS georeferencing method suggested by Roelfsema and Phinn (2009) allows its usage in benthic community mapping where photo samples taken underwater are used to verify the presence of habitat types on georeferenced satellite and aerial imagery.

Recently, this method has been used extensively in mapping of benthic communities for the purposes of the Habitats Directive in the Bulgarian coastal zone of the Black Sea. This includes studies of the distribution of Zostera seagrass meadows along the SW Black Sea coast (Berov et al., 2015; Holmer et al., 2016), as well as mapping of the distribution of lower infralittoral *Phyllophora crispa* macroalgal communities in a marine protected area (MPA) (Berov, pers.comm.). The developed methodology is probably easily applicable to studies of macroalgal communities in other European seas where the phytobenthos has similar structure – easily distinguishable large canopy-forming brown macroalgae (Cystoseira, Fucus), and smaller, but still identifiable from images epiphytic and basiphytic green and red macroalgal species. This includes surveys of the infralittoral communities of the Mediterranean, the Baltic Sea and the NE Atlantic coast, among others.

5. Future perspectives

The constant development of photo and video equipment opens new opportunities for improvement of the method. The use of the latest generation compact mirrorless or full-frame digital single-lens reflex camera (DSLR) cameras with high resolution (e.g. Canon D5 Mark II 21 megapixels camera) could almost double the image resolution up to 3337.5 pixels per cm^2, allowing an even more precise species identification. In certain cases where high-resolution images are not necessary, still image photography can be replaced with continuous 4K video filming, which provides frame grabs with 8.3 megapixel resolution and is an alternative method for faster image collection in scuba benthic surveys. The integration of digital photo sampling with data input from various sensors measuring physical, chemical and biological parameters of the environment (e.g. depth, temperature, salinity, light intensity, oxygen content, chlorophyll-a fluorescence), as well as automated integration of data, images and position in databases is another possibility for future improvement of the capabilities of scuba diver surveys, and is currently being tested and developed (Berov, 2012).

Acknowledgments

The work in this study was funded by the National Scientific Fund of Bulgaria, grant DO012/218/08. The authors would like to express their gratitude to members of the Laboratory of Marine Ecology, IBER-BAS that took part in the scuba and field work during this study.

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doi:10.3723/ut.34.021 Underwater Technology, Vol. 34, No. 1, pp. 21–30, 2016 www.sut.org

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Technical Paper

Fishing traps in western Sweden, location, type and frequency: underwater survey and investigation from Lake Gärdsken, Alingsås, Sweden

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Received 1 August 2016; Accepted 23 September 2016

Abstract

Fishing traps are perhaps one of the least studied categories of archaeological remains in Sweden. Since at least the Mesolithic (10 000–5 000 BP), use of systematic fishing structures to harvest the sea of its resources is evidenced in the archaeological record. Such structures are often found in lakes, rivers and estuaries. Relatively often, Bohusläns Museum has, during underwater archaeological surveys, discovered previously unrecorded fishing traps that often fall within the time frame of Middle Ages (11th to 16th centuries) to the modern day (19th to 20th centuries). Such structures, therefore, are not just a peculiarity but more a regularity – in that they have had a widespread use in Swedish culture and livelihood. One such example of this is from Lake Gärdsken, Alingsås. Alingsås is mentioned in the written record from at least the 1300s although it not implausible to assume that the area had been settled previous to this. In Sweden, fishing has not only constituted a pastime or a profession, but has served as a complement to the household. Farmers for example, would often fish to support their meagre income or diet. Although fishing traps have a widespread use, form and geography, all have the same function – to catch fish. This article includes the case study of Lake Gärdsken, Alingsås. Bohusläns Museum (the provincial museum of the county of Bohuslän) has undertaken several archaeological investigations in the lake since 2009.

Keywords: fishing traps, fast fiske, Bohusläns Museum, archaeology

1. Introduction

Fast fiske is a Swedish term for stationary fishing traps; they are structures built for a specific purpose that have a fixed size and shape, and are, for the most part, immobile. In this article, the author defines and describes some common types or styles of *fast fiske*, how they are constructed and where they can be located. This article is based on current inland environments and how they have been used by the common people (*allmoge*) for subsistence. As an example, the case study of surveys and investigations conducted in Lake Gärdsken, Alingsås from 2009 to 2015 will be used. Furthermore, the article discusses how these results and those of recent archaeological investigations can be used towards the discovery and investigation of even more sites.

2. Fishing traps (*fast fiske*), what are they and how have they been used?

Fast fiske can be translated in English as weirs, pots or nets. Depending on the geographic region and usage, fishing traps can be described by various names and terms. These are based on local practices, tradition and their origin; for example the term *fast fiske* can also be referred to as *fiskegårdar* or *fiskeverk* (Nilsson, 1969). Within Sweden, such structures have been used extensively in inland waters, and some have also been used in the sea. Traps are usually constructed of leading arms (*ledarm*) that end in some form of catchment area (*fångstrum*). *Fast fiske* is a method that has a long history in Sweden; it has been used to create a source of income, pay taxes and provide a complement to the daily household.

Fishing traps, however, are not specific to Sweden. Traps of similar nature and construction have been discovered throughout Europe. They have a similar form and function to those found in Sweden;

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examples include, Stone Age weirs with woven baskets in Denmark and medieval weirs in Ireland, England and Brittany in France. These are of similar construction, form and function to Swedish examples, with leading arms made from wooden poles or stone walls that funnel fish towards some form of catchment area (Becker 1941; Bernard and Langouët 2014; Christensen 1997; Daly, 2014; O'Sullivan, 2013).

2.1. The common (allmoge) *typology*

Fast fiske have a long tradition of being used extensively in shallow protected inland waters (Nilsson, 1969). Traps in such protected waters are most commonly *katsa* (plural: *katsor*), constructed with leading arms and catchment areas. In flowing water other types of traps have been employed, for example, *kista/mjärde* and *ryssja* (plural: *kistor/mjärdar* and *ryssjor*). Construction methods for all traps are dependent on several factors, such as whether they are situated in still or flowing water, the target species, the availability of material and local or common practice (Ekman, 1918; O'Sullivan 2013). Despite this, most fishing traps are constructed using the same simple fundamental principles, that is, a tightly interlaced and poled construction made up of leading arms or barriers that funnel fish into some type of catchment area or cage (*fångstkammare*) (von Arbin, in press; Eriksson 1993).

Names for the different types of fishing methods are numerous, and it is possible that a single method can have varying names depending on region or tradition (Møller, 1953). Through written historical material, it is known that the Finnish imported *katsa* was a common fishing method throughout 'middle Sweden' (*Mellansverige*) during the 16th to 19th centuries. During the 20th century, the method began to fall into disuse and was regarded as old-fashioned or outdated (Ulfhielm, 2005; Bodin, 2004a; Bodin, 2004b). The *katsa's* demise is probably a result of changing Swedish society and culture during the last few centuries. A shift towards industry and mass production, the cheaper price of fishing tools and construction materials, and changes in Swedish fishing laws all contributed to this (Ekman, 1918).

2.2. Katsa

A Finnish method imported to Sweden, the traditional *katsa* (Finnish: *kattisa*) is constructed of a leading arm ending in a single or several catchment areas (Hagberg, 1973; Rosén, 1955). Its arm is constructed in the same way as a wooden fence would be constructed on land. It is positioned so that it extends perpendicular from the shore (Claesson, 1937). Lengths of thin poles are woven together in sections, transported out to the lake and fixed in place with poles of larger diameter. Tree branches secured tightly between upright poles can also be used to construct a leading arm (Claesson, 1937; Nilsson, 1969).

Fish are thus tricked by the leading arm (which they believe is the shoreline) and swim into the catchment areas through narrow openings. Construction of the catchment areas are of similar design to the leading arm (Figs 1 and 2). Fish caught in the trap are unable to escape and can be either collected with a net or speared at the leisure of the fisherman (Bodin, 2004a). Remains of *katsor*, aside from those discovered archaeologically, have often been found in combination with low water levels, when the network of poles are clearly visible (Andersson and Björklund, 2006; Arwidsson, 1937).

2.3. Mjärde (or tina)

A *mjärde* or *tina* (pot or cage) is often a cage-like construction small in size, around 1–2 m, predominately used in inland waters. Construction for the most part is of wooden ribs or other wooden materials and so they are not collapsible (Modéer, 1939). More recently, they have been constructed using metal netting around either a wooden or metal frame (Fig 3). Fish are led into the *mjärde* via small cone-shaped entrances. As a complement to a *mjärde*, leading arms built in the same way as a *katsa* could be employed to drive fish in towards it; this structure is often called *mjärdestånd* (Rosén, 1955). To retrieve the catch, a *mjärde* is removed from the water and emptied. As with other types of *fast fiske*, its construction is determined by the individual who built it and local tradition (Ohlsson, 1981).

2.4. Ryssja

A *ryssja* is a fishing trap that utilises a long cone-shaped net (or in prehistory a woven basket) held open by rings of varying material (Becker, 1941; Pedersen, 1995). Modern *ryssjor* are collapsible, but when placed in flowing water the pressure of the water holds it open and outstretched (Fig 4) (Modéer, 1939). *Ryssjor* have one to several cone-shaped entrances along their length, ending in a catchment area often termed *fiskhuset* (fish house). Its construction therefore allows fish to freely swim in but denies escape. As with other *fast fiske* methods, *ryjssor* often use leading arms to direct fish into the trap. These are usually constructed similarly to those of *katsor*. Two arms are used to funnel fish towards the trap, though the trap can also have several arms or arms that create 'processing areas' directly in front of the entrance (Gyllenborg, 1770).

Usage is not just confined to inland waters, as *ryjssor* have been used extensively in the sea especially

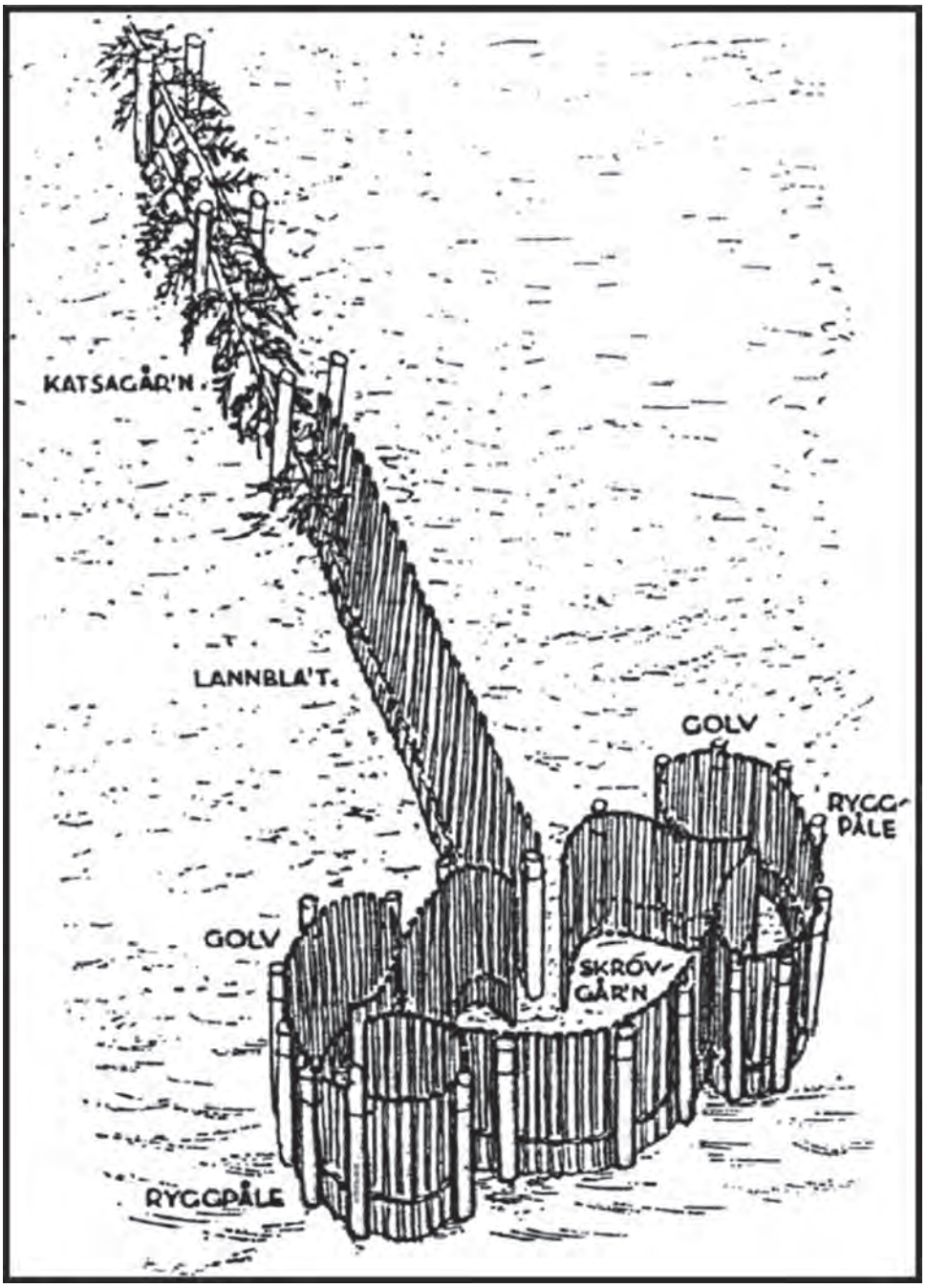

Fig 1: Drawing of a *kasta* by Claesson (1937).

around Sweden's southern coast (Arwidsson 1930; Møller, 1953). Evidence of the *ryssjan's* precursor can be found in the Low Germanic words *ruse* and *håmma,* and the French word *rusche.* This method probably arrived in Sweden from Germany or France, possibly via Denmark during the early medieval period (Arwidsson, 1937; Modéer, 1939; Rosén, 1955).

2.5. Fishing traps of Bohusläns Museum

Despite the fact that remains of fishing traps are likely most numerous in Sweden, relatively few traps have been investigated archaeologically. During the last few years, Bohusläns Museum (the provincial museum of Bohuslän) has discovered traps in several regions around Sweden, for example: Lake Åsunden, Ulricehamns kommun (von Arbin, 2006), Arvika sund, Arvika kommun (von Arbin and Wallbom, 2004), River Tidans mouth, Mariestads kommun (von Arbin and Lindström, 2005) and Lindholmen, Lidköpings kommun (von Arbin, 2015).

One exceptional site in Motala Ström (Motala River) has been investigated more intensively than the others. During 2003 and 2010, Bohusläns Museum undertook more detailed investigations of the Motala system of fishing structures (von Arbin, in press). However the museum, is not the only institution to have investigated such structures (Ulfhielm,

Fig 2: A photo of a contemporary *katsa* made from pine slats 'sewn' together. The fisherman is using a net to extract the catch (after Rosén 1955).

Fig 3: A photo of a modern day *mjärde*, placed in amongst the reeds in shallow water (after Rosén, 1955).

2005; Wallbom, 2011); the oldest find of a fishing structure in Sweden was discovered by Södertörns högskola (Södertörns University) in 2012. Located in Verkån (Hanöbukten), Blekinge it was carbon dated to 9 000 BP (Södertörns högskola, 2012).

2.6. Where and how they can be located

Based on the findings and research of the last few years, the author is attempting to develop a model for the discovery of fishing structures in the modern-day environment. Whether an area is developed or if it is in its natural state does not predict or exclude the presence of fishing traps. A plan must first be envisaged to incorporate a range of ideas and factors: how did the landscape previously look? How was it settled? What does the environment look like today compared with before?

Based on archival research, studies of historical maps, region or place-name nomenclature and the natural environment, the possibility of finding fishing traps within a proposed location can be determined with relative success. Factors such as fish density and movement, water flow and sediment type all play a role as to whether a trap is built or not, or what method is employed. The fishing technique employed, and therefore the likelihood of its rediscovery archaeologically, also depends on what type of environment it was built in. In addition, any evidence of their usage in prehistory must be taken into consideration; for example are there Stone Age settlements in close proximity?

Based on recent archaeological and public finds, fishing traps have more often than not been found in easily accessible areas. This is most probably attributable to access – close to a shoreline that enables easy retrieval of a catch and easy access for annual repairs. The processes mentioned earlier were employed during the latest survey in Lake Gärdsken, Alingsås in 2015 to determine the likelihood of fishing structures existing within a proposed development area.

3. Case study: archaeology in Gärdsken, Alingsås

Gärdsken is a narrow and shallow lake situated directly south of Alingsås city (Fig 5). It is approximately 1 km long with a maximum depth of about 10 m. Its sediment composition at river entrances

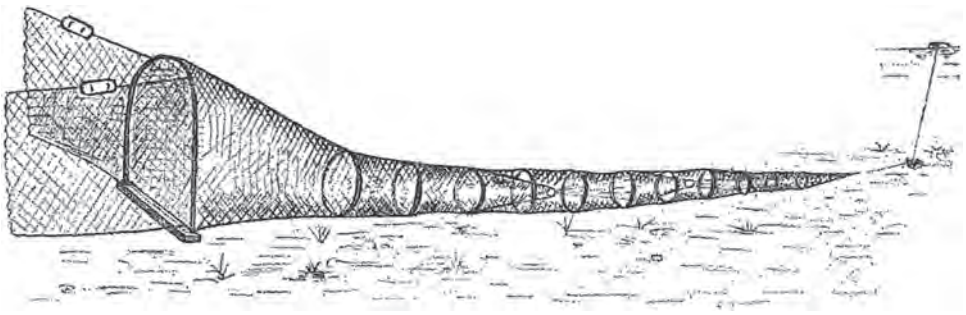

Fig 4: Drawing of a typical *ryssja* made of net (after Modeér 1939).

consists mainly of soft silt, and plant detritus often overgrown with reeds. Sediment composition becomes successively more stable towards the middle of the lake.

Gärdsken is interconnected to a major lake and river system called the Säveån catchment area. It is connected to the catchment area via Gärska ström in the north and the lake Lilla Färgen in the south via Forsån (Fig 6). Forsån and its mouth into Gärdsken have been the primary area for archaeological surveys and investigations in Gärdsken. Forsån is a small river, a mere 5 m–6 m wide and 2 m deep. It is approximately 1.3 km long with a slow northward flow. Sediments within the river mirror that of Gärdsken and its banks are covered by thick reed belts.

3.1. Archival research

Alingsås has been known since the middle of the 1300s when it was called *Alinsxaas*. A hypothesis for the name Alingsås originates from a combination of a prominent ridge (*ås*) and a road to the *alingar* from Ale härad (district), hence *Alings-ås* (Sawyer, 1985). During the middle ages, Alingsås was a significant trading site undergoing a substantial period of expansion (Sawyer, 1985). Control of trade during the middle ages was of foremost importance, and battles for strategic regions between the Swedish and Danish were commonplace. *Stora Gatan* (modern-day Kungsgatan, or the Kings road) was the major road to Alingsås; it followed Säveåns catchment area out to the sea via Göta älv (the river that flows through modern day Gothenburg) and was a vital route for travel and trade (Sawyer, 1985). The inhabitants of Alingsås and the surrounding region most probably had diverse subsistence and income sources. Aside from fishing, the raising of cattle, hunting and farming all played a significant role towards a household's income and sustenance. Alingsås city was founded during the 1600s at the same time as Gothenburg, receiving its city privileges 21 September 1619 (Andersson and Björklund, 2001). Fishing within Säveåns system has been of significant importance throughout history. Evidence of fishing for salmon, trout, eel, pike, perch and bream have been found at Stone Age sites in the region (Danielsson, 2008). *Fast fiske* has therefore most probably been used intensively in the region at least until the early 1900s.

Historical cadastres from the 1500s also provide information regarding fishing, for example certain farmers could even pay their taxes in eel (Sawyer, 1985). In modern history, fishing traps have also been located, more by accident than design. Within the region fishing traps have been located during periods of low water levels. For example during the 1920s and 1930s a *katsa* was documented in Lake Ömmern by Alvar Bengtsson (Andersson and Björklund, 2006).

Evidence of fishing traps can also be connected to the occurrence of *gårdsfiskare* who would have had a contract with a land owner to provide fresh fish in return for land or other benefits. Fishermen in Storeberg, Kållandsö west of Lidköping had a contract whereby they could retain half of the catch whilst the other half went to the landowner as payment (Nilsson 2013). Aside from fishing rights, a *gårdsfiskare* could possibly lease land and forest from the landowner. Historical evidence for the use of fishing for subsistence or employment in Alingsås can be found in archival records. These can be references to *gårdsfiskare* or farmers who had fishing as a side-line. For example, an eel fisherman is named in a business contract from 1694 between Anders Andersson and Kilanda säteri (manor) (Andersson and Björklund, 2001; Andersson and Björklund, 2006).

Past and present place names and nomenclature also provide clues to the existence and location of fishing traps. Terms incorporated into names – such as *verke* (a jetty with openings for *mjärdar* or leading arms of *ryssjor*), *gård* (*fiskehuset*), *stäk* (a structure of poles in water to obstruct) or *vad* (fishing method using netting) – can help identify areas that could contain remnants of fishing traps (Modeér, 1939; Reynolds, 2015; Ståhl 1970). Examples of this incorporation are: Verkeån in Skåne; Kattisnäset in Åre kommun; Kattisträsket in Skelefteå kommun; Kassängsviken in Kils kommun; and Oshult in

Fig 5: Map showing Alingsås location in western Sweden. Scale 1:1 000 000.

Markaryds kommun (Hagberg, 1973). As previously mentioned, typology nonclementure and evolution also provide clues to their proposed geographical region, their origins and their possible form (*Kattisa* in Finnish; *ruse* and *håmma* in German; *rusche* in French) (Modéer 1939; Møller, 1953).

3.2. Archaeological work in Gärdsken and Forsån

3.2.1 Survey (*Utredning*) 2009

In 2009, Bohusläns Museum was contracted by Länsstyrelesen (the county administration board of Västra Götaland) to undertake a survey of Gärdsken,

Forsån, Gärdska ström and Lilla Färgen before the *kommun* (city council) could lay a water pipeline between Hjälmareds water plant in Lilla Färgen and Hemvägen in Alingsås. The proposed route was: Lilla Färgen, Forsån, Gerdsken and finally Gärdska ström (Fig 6).

A survey was conducted of areas deemed to be of significant archaeological interest, which were the mouths of Gärdska ström and Forsån, Forsån between Gerdsken and Lilla Färgen and where it would reach land in Lilla Färgen. Methodology for the survey consisted of visual surveys of the entire survey area, whereby two divers searched the area visually using through water communications. The dive leader shadowed the divers in a small inflatable boat and used differential GPS to measure in finds. The survey resulted in 13 groups of poles driven into the sediment in Forsån and its mouth in Gärdsken. Based on their degradation and form, they were deemed to be archaeological remains and thus given the status of *fornlämning* (ancient monument) under Swedish law (Gainsford, 2009).

3.2.2. Preliminary investigation (*Förundersökning*) 2012

As a result of plans for a water pipeline and the preceding survey of 2009, Bohusläns Museum was contracted in 2012 by Länsstyrelsen to undertake a preliminary investigation of those previously discovered sites affected by the planned construction. Sites that were investigated were Alingsås 264, 265 and 266. However, during the investigation, a previously undiscovered site was found in the same area, Alingsås 281 (Fig 7). Investigation included visually recording the sites, measuring poles and structures with differential GPS and digging test pits to better understand their structure. Dendrochronological and carbon dating samples were taken. Carbon dating analysis is a method for measuring the quantity of carbon-14 isotope remaining in an organic material. This isotope is constantly being replenished and the amount in the atmosphere varies over time. When organic material dies the carbon-14 isotope breaks down at a measurable rate allowing it to be dated against a predefined curve.

Results of the investigations showed that Alingsås 266 is a catchment area consisting of 20 or so poles dated by carbon dating to the period 1720–1820 (2σ, 95%). Alingsås 265 is approximately 60 m long and consists of a leading arm that finishes in a circular catchment area upstream in Forsån. Its remaining structure comprises ~30 thinner and 2 thicker poles. Carbon dating analysis provided a date to the period 1720–1820 (2σ, 95%). Alingsås 264 remains constitute a leading arm and several circular catchment areas. The leading arm is

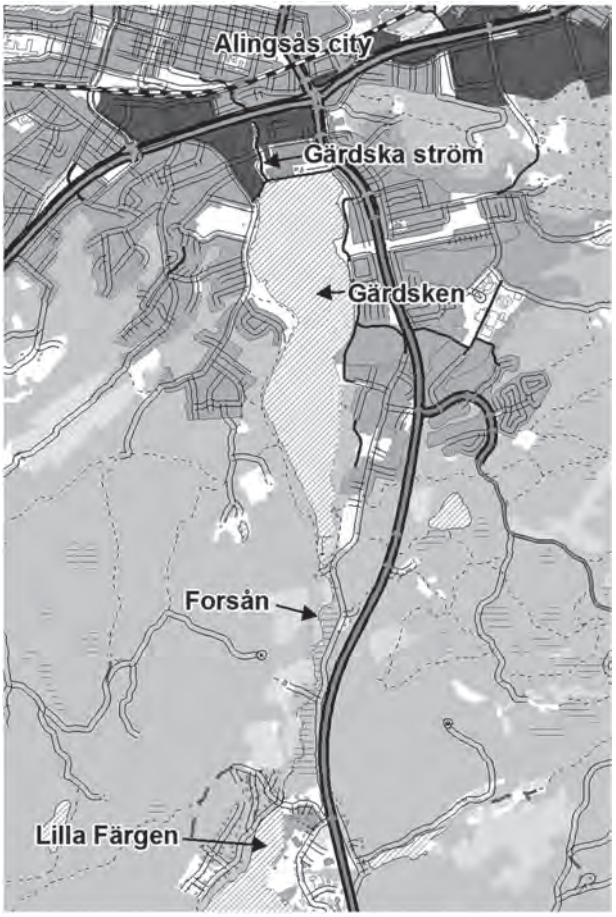

Fig 6: Map showing the various lakes and rivers covered in the archaeological surveys and investigations. Scale 1:7 500.

constructed of smaller driven poles circa 2 cm–3 cm in diameter. Catchment areas are evidenced by ~30 poles with a diameter of circa 10 cm – 15 cm; these are most probably the supports for the woven fences. Results from carbon dating analysis provided a date to the period 1660–1820 (2σ, 95%).

Alingsås 281 is made up of a leading arm and several circular/petal shaped catchment areas. It is constructed of thinner wooden poles that have been woven together with branches. Larger equidistant poles support the structure on one side (Fig 8). This trap was extremely difficult to locate since it was visible only a couple of centimetres above the bottom. A carbon dating analysis provided a date to the period 1660–1880 (2σ, 95%). Samples taken for dendrochronological analysis could not be dated because of the low number of datable tree rings and a lack of a curve for Juniper (Gainsford, 2013).

3.2.3. Survey (*Utredning*) 2015

In 2015, Bohusläns Museum was once again contracted by Länsstyrelsen to conduct a survey in the southern part of Gärdsken (Fig 7). Parts of the survey area had already been surveyed and investigated in 2009 and 2012, and as such were disregarded.

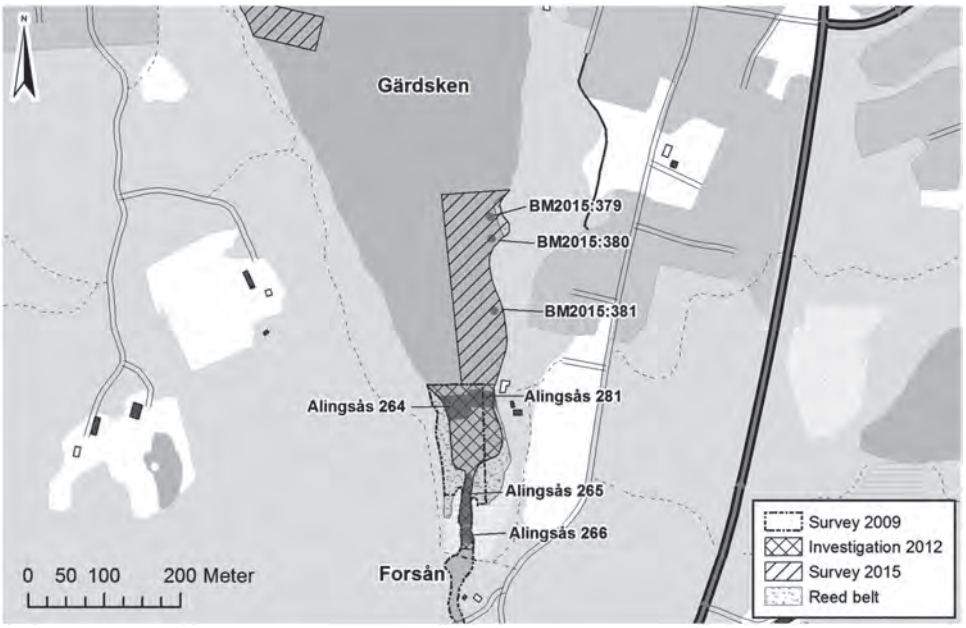

Fig 7: Map showing archaeological work conducted in southern Gärdsken. Scale 1:30 000.

Fig 8: Underwater photos of Alingsås 281; on the left is the leading arm and the right a catchment area. (Photo: Delia Ní Chiobháin Enqvist, Bohusläns Museum.)

The survey was in response to the *kommun*'s plan to lay a water pipeline over Gärdsken. Survey was concentrated to areas deemed likely to contain archaeological remains. Based on this and previous experience, areas close to the shoreline were prioritised. Towed diver searches, visual searches and a side-scan sonar survey of the entire survey area were used to locate anything of archaeological interest. As a result of the survey, three new previously undiscovered fishing traps were found (BM 2015:379, BM2015:380 and BM 2015:381 – see Fig 7). Samples for carbon dating were taken from all three sites. However, the results were varied. In combination with carbon dating analysis, their state of deterioration was taken into consideration.

BM2015:379 is an area of lakebed of circa 20 cm – 30 m diameter containing two groups of poles, each 6–7 cm in diameter. Poles are visible 4 cm – 5 cm to 30 cm – 80 cm over the sediment horizon. A calibrated carbon dating analysis provided a date of the periods (2σ, 95%) 1685–1735, 1805–1930 and post-1950. Based on the level of deterioration, the latter period should be disregarded. The structure has in all likelihood been in use during the periods 1685–1735 or 1805–1930. It was, however, most likely built before 1850 and therefore *fornlämning*.

BM2015:380 is a constellation of ten or so pine slats (rectangular in cross section, circa 2 cm by 3 cm), driven into the sediment and forming a tight wall visible for a length of circa 5 m (Fig 9). Construction methods similar to this have been witnessed previously in the river Tidan, Mariestad 2007 – a site dated to the early medieval period (Bergstrand, 2008). Since the pine slats in Gärsken are perpendicular to the shoreline and quite shallow, they most likely form the remains of the

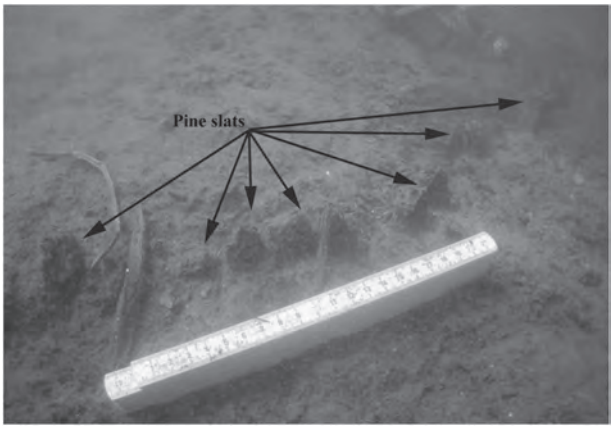

Fig 9: Underwater photo of the pine slats of *fornlämning* BM2015:380. (Photo: Delia Ní Chiobháin Enqvist. Bohusläns Museum.)

leading arm of a *katsa*. Carbon dating analysis provided dates within the periods (2σ, 95%) 1530–1550, 1635–1670, 1780–1800 and 1945–post-1950. As with BM2015:379, this site is deemed to be *fornlämning*.

The site BM2015:381 is an area of tightly driven pine slats similar in design to BM2015:380. The slats are significantly degraded and are of similar size and cross-section to BM2015:380. Within the same vicinity, there are also poles of 5 cm diameter. Carbon dating analysis provided a calibrated age (2σ, 95%) to the periods 1690–1730, 1810–1920 and post-1950. As with the previous two, this site was also deemed to be *fornlämning* (Gainsford, 2015).

4. Conclusion

Fast fiske has been a common fishing method from Sweden's prehistory until the last century. Unfortunately this area of archaeology has not been investigated to its full potential, as research within maritime archaeology tends to be largely shipwreck dominated. Over the last few years, in conjunction with planned contract archaeology, a significant number of fishing structures have been located in western Sweden. These structures are quite often located within areas that were previously thought not to contain any archaeological remains, let alone fishing traps. It has been shown, however, that even small lakes with no mention of fishing in the archival material have been used intensively, such as Lake Gärdsken. The area around Forsan's mouth and the southern area of Gärdsken are a prime example of a fishing complex in use during the period of 1600–1800, based on current carbon dating analyses.

Further studies and investigations of these structures have the potential to better improve knowledge of their function, material and construction. Since this area is a relatively poorly researched, the traps in Alingsås have the potential to contribute knowledge on a nationwide basis. Since such structures are from Sweden's relatively recent past, they can, in conjunction with research of archival sources and oral histories, provide information about taxation, daily life and sustenance. One question still remains: Has the area around southern Gärdsken only been in use during recent history, or does it have a longer tradition?

Based on current results, the site has possibly been used from the middle of the 1600s (Alingsås 281), although this does not preclude an earlier usage. As the site has been of such significance or value that a series of fishing traps have been constructed in a relatively small area, it is possible that the site has been used prior to current knowledge. Further archival and archaeological investigation is needed to clarify this. Site formation processes including sedimentation, removal or repair could mean that these structures may have been in use over a longer time frame. In order to better develop techniques to find such structures, models can be employed to determine the likelihood of their presence. These should be based upon archival research, oral histories, map studies, place or region names, an understanding of the environment and site formation processes, a knowledge of various fishing methods and how they were employed, and how the area was settled.

Acknowledgments

The author would like to acknowledge the help of Staffan von Arbin, Delia Ní Chíobháin Enqvist and Thomas Bergstrand of Bohusläns Museum, and Roland Peterson of Vänermuseet for all their help and ideas during fieldwork, as well as with the post-processing of data and compilation of reports.

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doi:10.3723/ut.34.031 Underwater Technology, Vol. 34, No. 1, pp. 31–38, 2016 www.sut.org

The closed circuit rebreather (CCR): is it the safest device for deep scientific diving?

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Received 12 August 2016; Accepted 20 September 2016

Abstract

The closed circuit rebreather (CCR) is not a new diving technology. From the late 1990s CCR units were commercially available in Europe, and increasingly more divers, and among them scientific divers, have been trained to use them. Even if many benefits exist for using CCR for all diving depth ranges, it is in the deep diving zone ranging from 50 m to 100 m of sea water where the main advantages to using this equipment exist. Using rebreathers does carry additional risks, and these must be mitigated to ensure safe usage. A standard for CCR scientific diving has existed for many years in the USA, and the levels of expertise within the European scientific diving community are now sufficient for a European standard to be established. National legislation for occupational scientific diving in many cases excludes CCR diving, which can limit its use for scientific purposes. This paper suggests that, where possible, legislations should be allowed to evolve in order to include this type of equipment where and when its use has direct advantages for both the safety and the efficiency of scientific diving. This paper provides a brief description of the fundamentals of closed circuit rebreather diving and outlines the benefits that its use offers diving scientists. Special attention is given to safety issues with the assertion that the CCR concept is, if strictly applied, the safest available technique today for autonomous deep scientific diving purposes.

Keywords: CCR scientific diving, mixed gas diving, diving safety, deep diving

1. Introduction

The closed circuit rebreather (CCR) is not a new diving technology. The concept of rebreathing gas underwater has been traced back to at least 900 BC (Bozanic, 2010) and the modern-day design remains based on pre-WWI models, an example being the Fleuss rebreather that was made in 1879. During both World Wars, many improvements were made to rebreathers based on their use for covert military actions.

The first electronic closed circuit rebreather, known as the Electrolung, was marketed in 1969. However, it was not until the late 1990s when electronic CCR started to be sold into the mainstream scuba diving markets, with the introduction of the BUDDY-INSPIRATION (now renamed the Ambient Pressure Diving's Inspiration CCR range). Modern CCRs for the European market are made by a small number of manufacturers, and their design and construction must follow the European Normative for rebreathers, EN 14143. The requirements contained within NBN EN 14143 (Bureau voor Normalisatie, 2013) are that rebreather technology using air as a diluent gas can be used to a depth of 40 m, while Trimix/Heliair/Heliox diluents should be used below 40 m to the maximum depth covered by the EN standard of 100 m. The technologies associated with CCRs continue to improve their functioning and use, with the latest developments including CO_2 sensors in the breathing loop, bailout valves and solid state oxygen sensors (Sieber, 2014).

CCRs do not produce bubbles except for very few during the ascent phase of the dive. Their main advantage for diving physiology is that they permit the diver to breathe a constant partial pressure of oxygen during the dive. A sodalime filter removes the carbon dioxide produced by human metabolism while an electronic feedback system controls the partial pressure of oxygen (ppO_2) available in the breathing loop controlling oxygen addition into the loop automatically if required.

The three main advantages that CCRs offer the scientific diver are the significant lack of bubbles, gas efficiency and the optimised decompression that constant partial pressure of oxygen permits. The lack of bubbles has been shown to reduce the

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impact the diver has on the marine life being studied and improve the quality of science being undertaken in environments where the diver's bubbles would physically disturb the ecosystems being studied. Moreover, and from a safety perspective, CCR technology (when used according to the rules) is based on built-in redundancy and operational procedures that can enhance the safety of the diver.

However, CCR technology can add new risks, oxygen and/or carbon dioxide toxicities can occur very rapidly when the rebreather is not working properly or if the diver did not setup the equipment according to manufacturer specifications. Gas choice is of primary importance and proper training is the key factor for mitigating these risks. The equipment must be handled with care, and it is important that the diver adopts new approaches to how they undertake their diving when moving from using open circuit to CCR.

Much of the scientific use of CCR technology with mixed gases has been based on extending the underwater exploration range to limits that far exceed those possible when using typical scuba equipment. One of the first researchers to take advantage of the new technologies was the ichthyologist Richard Pyle from Honolulu, who used CCR equipment to study fish found in the mesophotic zone. It is not the purpose of this paper to provide a full list of all the studies that have employed CCRs, but many applications exists in behavioural sciences such as: Collette (1996) looking at fish behaviour; Lobel (2009) studying underwater acoustic ecology; and Tomoleoni et al. (2012) and Tinker et al. (2007) who used CCRs to facilitate the capture or recapture of sea otters. Moreover, Hinderstein et al. (2010), Sherman et al. (2009) and Rowley (2014) used the advantages provided by CCR deep mixed-gas diving to study mesophotic coral ecosystems.

In Europe, it is widely accepted that diving for occupational scientific purposes should be limited to a maximum depth of 50 m when diving open circuit scuba using air. Beyond that depth, mixed gas technology is used in order to overcome the problems generated by nitrogen narcosis and to achieve acceptable gas densities that reduce the work of breathing (Mitchell and Doolette, 2013). The current situation in Belgium is that the scientific diver is advised to use rebreathers for diving as soon as there is a demonstrable added value for the scientist or for the quality of the science undertaken. Nevertheless, in many European countries, the use of mixed gas diving in support of underwater science is still in its infancy, and in some cases the use of rebreathers for occupational diving may not be permitted by law. In France, the capability to use rebreathers in scientific diving was initiated in 2014 (L'Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail (Anses), 2014). However, the administrative and human resource challenges will probably be numerous and will more than likely be similar to the challenges outlined by Dokken (2006), who described how rebreathers became accepted for use in science diving in the USA.

For deep scientific diving, the CCR technology brings additional benefits over open circuit, such as reduced mixed gas requirements because of significantly higher gas efficiency leading to much lighter equipment to carry on expedition or use during the dive. In closed circuit diving, the breathing mixtures are different to open circuit and are usually set to deliver a lower equivalent narcotic depth (END), which allows better quality underwater work to be undertaken. CCR diving also brings a lower risk of making errors during decompression since the units alter the gas mixtures internally, negating the need for any physical gas switches by the diver. The negative aspects of CCR diving are the high costs of the rebreather unit itself, as well as the financial and time costs associated with the training required to be able to use them for the scientific research diving (Lang and McDonald, 2012). Careful planning is key to ensuring a safe diving activity, and special attention is needed when considering the bailout gas strategy for all aspects related to oxygen and carbon dioxide toxicities, gas density, inert gas narcosis decompression stresses.

The following section focuses on the safety issues related to the training, dive planning and operational use of mixed gas CCR technology when applied to scientific dives between 50 m and 100 m depth. The discussion also considers the practical application of dive planning rules, including gas choice and bailout strategies.

2. Methods

2.1. Training

All rebreather manufacturers require that training is taken prior to the purchase and use of their units by the diver. This training is the most important step to ensure the efficient and safe use of CCRs by a diver. If rebreather diving is being considered for a group of divers who will then work together in the future, then the group should consider undertaking the same training courses together. This approach may be time-consuming, as planning for a minimum of two years of preparation for a team prior to any scientific diving projects starting may be advisable. Rebreather training is commonly divided into a core course that is generic to all rebreather diving, and

then a unit-specific course dedicated to the particular make and model of the rebreather that will be used. The diver is, therefore, only certified to use one type of rebreather. Should the diver change unit type, they would be required to undergo additional training that is specific to that new unit.

In addition to being unit-specific, rebreather training is also limited to a given depth of operation. Most training agencies have three levels of rebreather qualification; these tend to be defined by the maximum operating depth (MOD) that the training supports. The actual MOD limits differ slightly between training agencies but generally MOD-1 training supports rebreather diving where the diluent gas is air diving to maximum depths of 40 m, the MOD-2 level uses trimix gas mixtures as the diluent to maximum depths of 60 m, and the MOD-3 level uses a trimix diluent to a maximum depth of 100 m. Once qualified at one level, the diver must usually achieve at least 50 hours of diving on the unit before starting the training for the next level.

Training usually begins with an initial introduction to the theoretical considerations of diving physics and gas physiology before the diver can begin to learn to use the diving unit in actual underwater operations. During the practical training, the diver is taught how to safely assemble and test the unit before diving. Because of the relative complexities of a CCR unit, evidence suggests that the diver is less likely to make mistakes during the setup if checklists are used to guide them through the process (Mitchell, 2014). In fact, many modern CCRs have checklists programmed into the display units with the diver having to follow them when preparing for a dive.

Once in the water, the diver is first trained in the normal use of the rebreather before being trained on actions to be taken in case of malfunction of various parts of the equipment. A rebreather is a more complicated piece of gear than normal scuba, and so equipment malfunction may be more likely to happen. Therefore, all rebreather diving should have an alternate source of gas – known as bailout gas – available. For the advanced MOD-2 and MOD-3 training levels, more consideration is given to adequate gas planning. This includes learning to control the psychological issues related to deep diving and escape procedures in case of rebreather malfunctions, and it may include training that is based on bailing out to open circuit diving. At the advanced training levels, more emphasis is given to considering the various possibilities to continue breathing from the main CCR breathing loop while safely solving problems that have occurred.

Following Lang and McDonald (2012), the nature of occupational scientific diving could mean that the training undertaken should consider including some of the more common science-related tasks to be undertaken underwater. Ideally, the training should be delivered by a scientific diver who holds the appropriate CCR instructor certification. Some of the more important aspects of CCR training are dive planning, gas choice and bailout strategy for mixed gas diving.

2.2. Dive planning

The selection of the diluent gas is the first step when starting dive planning but is influenced or driven by knowing the dive site location and the planned maximum depth. The diluent gas is usually based on a mix of oxygen, nitrogen and helium (trimix) or oxygen and helium (heliox). The diluent gas could theoretically be a single inert gas or a mixture of inert gases, but it must, in practice and for safety reasons, contain some oxygen. The fraction of helium is defined when the END is known and the fraction of oxygen is defined by the maximum ppO_2 acceptable at the MOD of the dive. The computation of the END in the breathing loop of a rebreather is somewhat more complicated than for open circuit and will always result in a shallower END than when using open circuit for a given fraction of nitrogen. In the CCR sector, this mix is often blended as heliair, which is a mixture of just helium and air but is always hypoxic (i.e. containing a fraction of oxygen that is less than 21%). This is mainly because of operational simplicity, but also because oxygen control is provided anyway by the CCR.

After computing the END the resulting gas density must be taken into account in order to minimise the work of breathing. The work of breathing on a rebreather is influenced by its design (loop, CO_2 canister, position of the counter lung) as well as by the gas density. Assuming that the diver has not modified the design of the breathing loop, the present recommended values for gas density in the loop are below 5.7 g L^{-1} (Antony and Mitchell, 2016). This corresponds to breathing air at 30 m, with an absolute maximum limit of 6.7 g L^{-1} (air at 40 m). Maintaining the gas density below these limits will mitigate the risk of CO_2 retention and therefore hypercapnia.

It is a basic safety factor that bailout gases are always carried during a CCR dive. These are defined both in terms of the gas fractions of the three gases (O, He and N) and in the overall quantity of breathing gas required. To do this accurately, it is necessary to have estimates of the breathing rate of the diver expressed as their respiratory minute volume (RMV). Two different gases are usually planned: a 'bottom' gas and a 'decompression' gas. The fraction of oxygen on the bottom and decompression bailout gases are computed knowing the maximum ppO_2 allowed at the MOD of the dive and the depth

at which a decompression gas will be required. The fraction of helium in the bottom gas is computed using the permitted END, which also takes into account that the partial pressure of nitrogen should not build up at the moment of the gas switch and that an acceptable gas density is achieved. Similar calculations are needed for the fraction of helium, if any, in the decompression gas.

The volume of bailout gases to be carried is computed iteratively based on the basic dive parameters of planned bottom time and the resulting decompression obligation. However, the eventual volumes can be moderated depending on the choice of bailout strategy, which could be determined by a requirement that all divers are to dive completely self-sufficiently. Alternatively, some reliance could be allowed for a dive team bailout where gases could be shared, or even on gases that could be available at a decompression station deployed by the surface vessel.

After the selection of the diluent gas and bailout gases, the diver then needs to plan the amount of decompression that will need to be made and how the stops are staged. To do this, the CCR mixed-gas diver can use either dive tables or planning software that include decompression algorithm(s) for constant partial pressure of oxygen diving. Except the work done by the US Navy (Johnson and Gerth, 2001), there are not many tables that exist to support diving using constant partial pressures of oxygen in helium. VPLANNER or, more recently, MULTI-DECO (Vplanner +Bulhman GF) developed by HHS Software are the most commonly used software for determining decompression. Some CCR manufacturers provide decompression computers that measure the breathing loop partial pressure of oxygen in real time and continuously compute decompression for a given diluent gas composition. A further alternative is to use unlinked mixed-gas dive computers that allow set-points for constant ppO_2 computations to be made. Doolette and Mitchell (2013) evaluated the present-day use of decompression algorithms by technical divers. They concluded that even though the commonly used decompression algorithms were not validated, unlike the US Navy tables (Johnson and Gerth, 2001), the technical diving community is performing many thousands of dives safely, even though the incidence of decompression sickness remains unknown. Doolette and Mitchell (2013) further concluded that it remains unknown if these unvalidated decompression procedures are optimal.

2.3. Diving operations

Deep diving is always challenging because of the many aspects to be considered during the planning process. Examples include dive location and weather; local administrative requirements; length of the proposed operation (a single dive or a series of dives); accommodation and catering related to the length of the operation; the management of the quantity and quality of the breathing gases; the dive team; the safety diver; underwater communications; and the decompression support both underwater and onboard, if required by the diving regulations or if surface decompression (SurD) is going to be used. Some of these aspects are addressed in European Scientific Diving Panel of the European Marine Board (ESDP, 2011).

Planning and executing CCR diving at work will vary considerably with the diving location. For example, planning and operations for cold water CCR diving will be different to that carried out in moderate or warm waters (Bardout, 2016). The target dive site could be, for example, a natural rock wall, a wreck or isolated rocks on the sea bed, and in each case the diving procedures will differ. This, in turn, could influence the type and size of support vessel. The support vessel should be able to provide enough gas in quantity and quality for the diving operation to be completed safely. Basing the work on CCR diving only will reduce the quantity of required gas drastically, permitting the use of smaller vessels and lighter loads. All breathing gases supplied should fulfil the European norm UNI EN 12021:2014 especially for the oil content in the air that is used in any oxygen-clean apparatus, including at the blending stage. Finally, it is extremely important to verify the actual final gas mixes that have been blended; best practice is to do this using more than one oxygen and/or helium meter.

The level of competency qualification required of the members of the CCR diving team is usually linked to local regulations. At European level, there are scientific diver qualifications overseen by the ESDP (2009). Unlike what exists through the American Academy of Underwater Sciences (AAUS, 2013), there is currently no specific competency level or standard recognised by the ESDP for rebreather diving in Europe. At the national level, an occupational scientific diving organisation may be responsible for establishing the acceptable standards. For example, in Belgium certification from known training agencies that are recognised by the manufacturer of the rebreather is accepted. The same approach could be adopted by the ESDP when a future standards supporting rebreather use in scientific diving across Europe are being considered.

2.4. Safety of CCR mixed-gas deep scientific diving operations

Scientific diving activities are known to be safer than any other kind of occupational diving, at least

where decompression sickness is concerned (Dardeau et al., 2012). The study of Dardeau et al. (2012) was based on a dataset from the AAUS for the period 1998–2007; CCRs were in use by AAUS members during that period (Sellers, 2016). There is not much literature concerning the diving accidents resulting from the use of CCR, or any other types of rebreather outside the military sector (Louge et al. 2009). Trytkjo and Mitchell (2005), Lippman et al. (2011) and Fock (2013) examined the matter at different levels of approach. Fock (2013) examined deaths resulting from CCR dives within the period 1998–2010 and concluded that the risk of dying when using rebreathers appears to be 10 times what would be expected when using open circuit. The majority of the reported deaths were during what Fock defined as 'high risk dives' or which included 'high risk-behaviour'. Examples were entering the water with partially functional equipment or carrying insufficient bailout gases for an emergency.

Recently, Sellers (2016) extensively described the use of rebreathers in scientific diving operations at a number of American institutions. The study showed that rebreather dives represent less than 0.7% of the total numbers of dives operated. Based on the dataset examined, the non-fatal accident rate for rebreather diving was 6 for 15 767 dives. Moreover, it was possible from those data to isolate dives that were deeper than 58 m (the AAUS maximum depth limit for diving on air only) but undertaken using mixed gases. No accidents were reported for those types of dive and, since 2011, these deep mixed-gas scientific dives were operated more using CCR than open circuit scuba.

Some rebreather models can log data during the dive (Parker, 2014). The information that tends to get logged is: ppO_2, time, depth, voltage of the batteries, scrubber temperature (if measured), and the decompression obligations in addition to any set points selected by the diver and any alarms occurring during the dive. These data are valuable when examining what occurred in the case of any accident and are used to inform future training priorities.

3. Discussion

There are several rules or recommendations that CCR divers use when considering the correct fractions of oxygen and helium that make up the diluent gas to be used during a deep CCR dive. For instance, Lombardi and Godfrey (2011) recommend having a partial pressure of oxygen with a maximum PO_2 of 1.30 bar at the MOD in the diluent, while Mount and Dituri (2009) recommend a maximum of 1.00 bar at MOD. The idea behind this maximal ppO_2 in the diluent gas at MOD is simple. In the case of a hyperoxic loop, a diluent flush must be able to reduce its ppO_2. Therefore, having a lower ppO_2 in the diluent than the normal loop values of between 1.20 and 1.30 bar helps to reduce the resulting ppO_2 quickly while also using a lower volume of gas. Having less oxygen in the diluent also reduces the overall density of the gas mixture.

The composition of the inert gas fraction of the diluent gas is a source of discussion that lacks any definitive conclusions. Lombardi and Godfrey (2011) chose END values that ranged from 15 m to 50 m. Some of those values exceeded the recommendations of some training agencies, which propose an END value of 36 m (Mount and Ditury, 2009), or of some manufacturers, such as setting an END of 24 m for the depth of 100 m (Parker, 2016). Moreover, an END of 50 m results in a gas density that is well over the acceptable limit.

The narcosis effect of the diluent mix will further affect the judgment of the diver at depth, and this is certainly not desirable when both diving deep and working underwater. Not only will narcosis reduce the quality of the work, but in cases of an emergency the diver suffering narcosis will also have an increased reaction time with possible undesired outcomes. Diving with a diluent mix that does not satisfy the manufacturer's recommendations is dangerous behaviour and increases the risk associated with the dive.

The same simple rules also apply to the behaviour of the rebreather diver in relation to the oxygen cells used in the rebreather oxygen control system. The cells must be tested during any rebreather start-up and dive to confirm that they are working correctly. Making an oxygen flush at 6 m depth will give a good indication of the status of the cells. In the case of outdated cells (more than 18 months from their manufacturing date) or cells found to be out of working limits, the dive must be terminated and the cell(s) replaced before diving the unit again. Otherwise, there will be an increase in the risk taken for the dive.

The last point to be discussed is the correct choice and strategy for bailing out of a dive in an emergency. Bailout strategy can vary in two ways: the diver may choose to be fully self-sufficient on bailout gas, or the diving team of two or three divers may choose to share the bailout gas within the group, resulting in a lighter load during the dive for each individual.

In the first situation, the diver must carry throughout the dive a minimum of two extra cylinders – one bottom gas and one decompression gas. The size and number of bailout cylinders will depend on the

planned dive profile. The quantity of gas required must address the worst-case scenario of a bailout. This will be when the failure of the rebreather occurs exactly at the end of the bottom time section of the dive – in other words, when the decompression time is maximal. In the case of a complete failure, for example where the breathing loop becomes flooded with water or an inefficient CO_2 absorber, the diver must stop breathing from the rebreather loop and instead move onto open-circuit bailout. In less extreme events, such as total or partial failure of the electronics or the loss of a gas, the rebreather loop can still be dived in semi-closed mode, either on the diluent or on the bailout bottom gas. This mode type means that the dive can be safely completed using only a third of the gas quantity needed for the equivalent open circuit bailout.

When the self-sufficient bailout strategy is chosen, the diver can select a configuration that would include breathing the diluent gas as the first bailout gas, followed by an intermediate gas mixture. This would be then followed by breathing a decompression gas that could be used until reaching 6 m depth, where the loop could be breathed in pure oxygen mode, if not flooded or if the CO_2 absorber continued to work properly; this is because electronic control would not be required at those depths. There would still be an option of breathing pure oxygen in open circuit mode in the case of complete failure of the breathing loop. This configuration could make use of 6.8 L carbon 300 bar dive cylinders for the intermediate and decompression gas mixtures, and 7.0 L aluminium cylinders for the diluent and pure oxygen gases. However, when planning the volumes of gases required to support this configuration, consideration must be given to the fact that gases compressed to 300 bar do not follow the ideal gas laws. The Van der Waals interactions cannot be ignored above pressures of 240 bar and, instead, real gas laws apply and have the effect of reducing the assumed available volume of breathing gas.

Where it is planned that the bailout gases would be shared within the dive team, there is the obvious requirement that the divers remain together during the complete dive. Following Mount and Dituri (2008), a team bailout could be planned based on the three divers having sufficient bailout gases to support the ascent of 1.5 divers to the surface in open circuit mode. The three divers would each carry a pair of 11 L S80 cylinders: one cylinder would be filled with a bottom gas that should always be available to any of the three divers; the second would contain a decompression gas for two divers; and the third would be an intermediate gas for the third diver. The team would have to swap the cylinders between them during the ascent to support the diver having to bail out. The team bailout strategy is more optimal in terms of the number of cylinders that need to be carried per diver, but it does assume that only one unit during the dive has a problem requiring a full open circuit bailout.

The bailout ascent profile will depend on the composition of the bailout gases.

These are chosen in CCR deep mixed-gas diving following strict guidelines. The guidelines are based on the CCR diver having a bottom gas available that, when breathed on open circuit, would neither be hyperoxic or narcotic at the MOD of the planned dive. For example, a CCR dive that used air as the diluent to a maximum diving depth of 40 m, could use air as the bailout gas at that MOD. When diving deeper and using a mixed gas the ideal is to have the maximum possible oxygen fraction in the bailout gas to enable a maximum ppO_2 of 1.40 for the bottom gas and 1.60 for the decompression gas. For the remaining inert gas composition of the gas mixture, the strategy followed is to minimise the increase of ppN_2 to a target amount while lowering the fraction of helium in the gas. The ideal situation is to replace the helium with oxygen while keeping the same amount of nitrogen at the gas switch. This is usually not practical for something like a 100 m depth dive with a bottom time of 20 min while only using two ascent gases. It would, however, be possible with three ascent gases.

In practice, for a dive of 20 min bottom time at 100 m depth, the gas choice should be as follows. The initial diluent being used for the dive could be 8/67 (8% is the fraction of oxygen while 67% is the helium fraction, with the remaining part 25% being the nitrogen fraction of the mix; this mix would have an END of 23 m at 100 m). On initiating a bailout, the diver could switch to a bottom gas of 13/65, which during the ascent is then changed to a 25/45 mix at 45 m. At 20 m, the diver could change to a 50/20 triox mixture (triox gases that are a trimix with an oxygen fraction higher than 21%), followed ideally by a last switch at 6 m from triox to pure oxygen. In this case, the total decompression time during a bailout situation would be similar to the CCR time without bailout. Mount and Dituri (2008) published a table that can be used to compute the composition of bailout gases.

The scientific diving sector has the lowest incidence of decompression accident rates of all the industry sectors (Dardeau et al., 2012). This may, in part, be because of the education levels of the population in the sector, in addition to their ability to recognise when to not attempt or to terminate dives that are considered to be unsafe. There is, at

present, no evidence to support that the accident rates will change as or if the mean diving depth increases. Fock (2013) suggested that CCR diving risk is reduced significantly when all the rules are respected and the use of the rebreather is well understood by the user. In most of the accident cases reported, the causal factor was human error and not rebreather failure.

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doi:10.3723/ut.34.039 Underwater Technology, Vol. 34, No. 1, pp. 39–43, 2016 www.sut.org

Development of a mobile airlift pump for scientific divers and its application in sedimentological underwater research

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Received 8 August 2016; Accepted 9 September 2016

Abstract

To make the advantages of airlift pumps accessible for scientific divers working on geoscientific topics, the authors developed a mobile airlift pump that operates without any surface support. The device is powered by standard scuba tanks and has quite a slim design. Thus, it can be easily transported by scuba divers with lifting bags. The construction is based on the laws of Bernoulli and Boyle-Mariotte: a defined amount of gas supplied at the lowest point of a vertical, semi-closed system will expand while ascending and cause a negative pressure at the bottom. The development and practical testing was carried out in various lakes in Germany and in the Mediterranean Sea during fieldwork in the hydrothermal system of Panarea, Italy. There, chemical erosion led to sediment-filled cavities with diameters of several decimetres that are aligned along geological fractures. The removal of sediment is the main requirement to document the unique but covered lithological structures.

Keywords: Airlift pump, scientific diving, hydrodynamic excavation, Panarea

1. Introduction

The investigation of submarine geological structures is often hindered by sediment cover. A detailed analysis necessitates the removal of this decimetre-thick sediment layer and an established method for doing so is to use airlift pumps.

The principles of airlift pumps have been known since the end of 18th century, when Löeschner (1797) invented the first industrial airlift pump for use in underground mining. In professional diving, airlift pumps are used for excavations and cleaning processes, e.g. the removal of sediment from archaeological items. Usually, these devices are supplied with a constant gas flow from a supporting vessel. This ensures nearly unlimited operational hours of the device and advantageous suction-power potential. However, long supply lines are necessary to operate the airlift, causing severe problems for divers in currents and greater water depth.

In addition, air-powered suction sampling is applied by marine biologists to collect specific taxae from the seabed. In this case, the ejector is equipped with a sampling net to catch the individuals of interest (e.g. Linnane et al., 2001; Templado et al., 2010; Ringvold et al., 2015). To make the advantages of airlift pumps accessible for scientific divers working on geoscientific topics, the authors developed a mobile airlift pump that operates without any surface support.

2. Technical requirements and fluid dynamics

As a general concept, a mobile airlift pump had to be developed to work without any surface supply during operation. The pump will be operated by two to three divers at an operating depth of 5 m to 40 m below the water surface. Surrounding water temperature will range from 4 °C to 30 °C. The device must work as well in salt water as in fresh water environments and withstand respective types of corrosion.

The tool must be able to deal with sediments of various compositions and different grain sizes. This includes fine, adhesive clay and silt, abrasive gravel and any combination in between. Therefore, a

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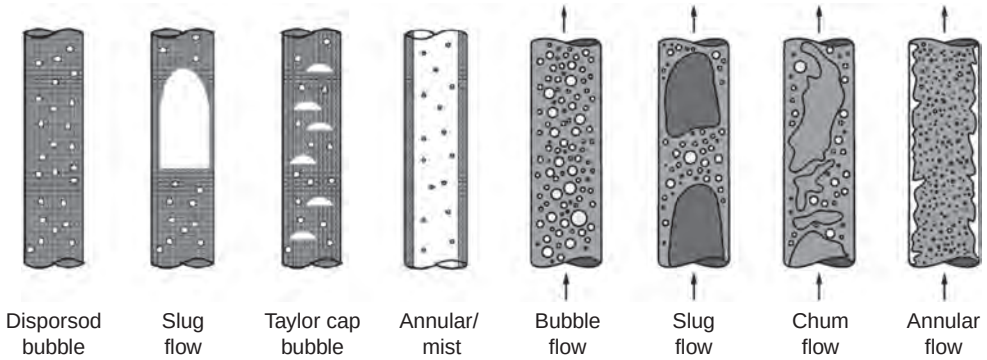

Fig 1: Various bubble types (left; USNRC, 2007) and types of flow (right; Mahrous et al., 2013) control the efficiency of the airlift pump. The annular flow represents the optimal mixture.

diameter of 50 mm to 300 mm at a rising height of 1.5 m to 5 m has to be applied to generate different amounts of suction power. The general grain size ranges from silt to fine-gravel. Air supply is realised by on-site reservoirs (scuba tanks). The optimisation of suction power and air consumption is the most challenging task in the complex fluid dynamic system that is the 'airlift pump'. Despite the grain size of the sediment and the technical parameter of the pump itself, the flow model is a central point. Inside the pipes there is a mixture of water, gas and sediment (multiphase flow). Especially regarding differences in the bubble-type (Fig 1), the amount of air in the mixture and the number of components in the flow are crucial topics for process optimisation. A continuous annular multiphase flow was found to be the most efficient. This means that as many small, similar shaped bubbles as possible have to be produced. Too large bubbles will cause the sediment to fall through the air-filled space. A small amount of air will be less effective.

3. Technical data prototype

The device is powered by three standard scuba tanks (15 L, 200 bar each) and has quite a slim design. Thus, transportation with normal lifting bags (~50 kg) by the operating diver is possible. The riser pipe has an inner diameter of 5 cm (2″) and a rising height of 3 m being lifted by a standard diving buoy to stabilise the system. The intake (suction hose) has a diameter of 36 mm and a length of 1.5 m to 3 m in the tested configuration (Fig 2). A long suction hose is beneficial as it ensures a sufficient distance between the operating diver and the ejector of the airlift pump. To keep the construction slim and unsusceptible to errors, its point of ejection is kept simple and without a sediment chute to carry the ejected material away. This means that the positioning of the airlift at its place of deployment is crucial. If there is any bottom current, the tool has to be placed downstream – away from the working area. Otherwise, the ejected material will fall back onto the working area or the divers.

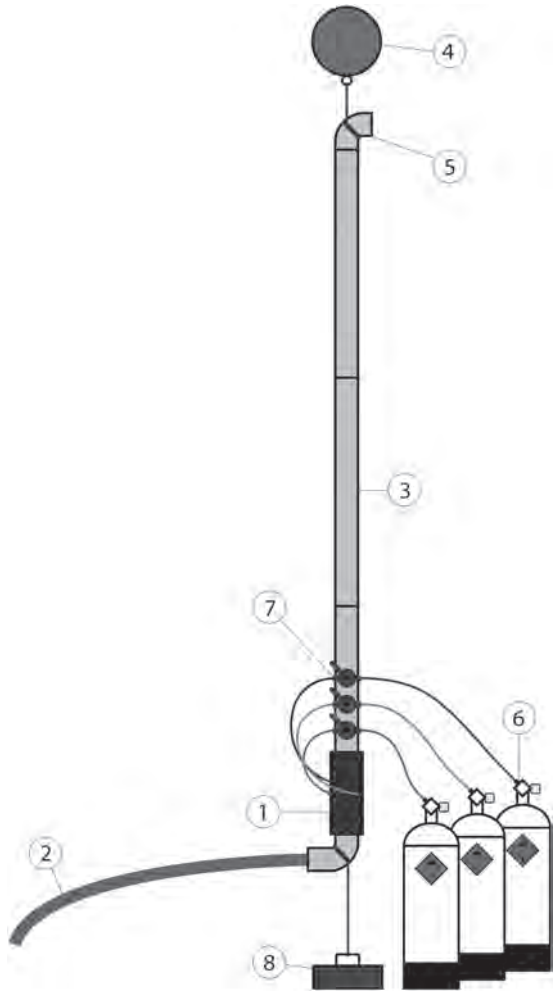

Fig 2: Technical model of the current prototype version. Major components: (1) mixing chamber gas injection, (2) suction hose, (3) riser pipe, (4) buoy, (5) ejector, (6) reservoir with supply-lines, (7) control panel, (8) counterweight.

The pump is fixed by counterweights of 16 kg. Approximately 10 bar working pressure is constantly derived as low pressure from a first stage regulator being installed to the air reservoir. However, an on/off set-up was deployed to keep the system as simple as possible.

One device could be manufactured as a rough version at costs of approximately €500, excluding the scuba tanks and regulators. The theoretical background of the construction is rather simple: gas is supplied to a vertical, semi-closed system at its lowest point. According to the laws of Bernoulli and Boyle-Mariotte, it will expand while ascending inside the tubing. The displaced water causes a depression at the suction hose. As the present system is open on both sides of the tubing, a continuous flow is induced.

The construction is composed of three main groups of components (Fig 2):

1. a mixing chamber where the gas is injected (connections arranged in one level every 120°);
2. a suction hose that is connected to it; and
3. a riser pipe in which the multiphase mixture (water, gas, sediment) ascends and is ejected.

The present version is characterised by a rising height of 3 m, which causes a pressure difference of 0.3 bar between the suction hose and the sediment release. Although this version is optimised for the removal of sediments with grain sizes from clay (< 63 µm) to fine gravel (2–6.3 mm), other fractions would be possible by modifying the dimensions; the larger the rising height, the larger the suction power and thus the larger the transportable grain size. The optimisation of this correlation is very complex and depends on the rising height, the sediment type, the shape of bubbles and some other parameters. A detailed discussion would go beyond the scope of this article.

To start the airlift, the operating diver turns on all three air-supply lines. The use of single supply lines is not recommended: the mass-flow is limited at each supply line and is optimised for a three-tank construction. Using only one or two tanks lowers the effectiveness of the airlift. The suction power is generated and the excavation can be conducted (Fig 3). After finishing the cleaning or at a critical pressure in the reservoir tanks, the work has to be stopped and the whole system has to be flushed by clear water to prevent the clogging or reflux by or of sediment. Finally, the system is shut off, deconstructed and transported to the surface.

4. Results

Field tests were carried out in various lakes in Germany for engineering purposes, as well as in the Mediterranean Sea during fieldwork on submarine hydrothermal structures at the coast of Panarea, Italy.

The mapping of small-scaled hydrothermal fluid discharge structures is a good example of a typical application of the airlift pump. The discovery and sampling of such fragile items (Fig 4) would be nearly impossible without this technical aid. The samples give evidence for early diagenetic stages of sedimentary fluid escape structures. The locations in Panarea are characterised by notable volcanic activity. Hydrothermal alteration in particular forms the rock surfaces as aggressive fluids discharge at temperatures of around 130 °C. The resulting chemical erosion and precipitation lead to sediment-filled cavities (Fig 5) with diameters of several decimetres that are aligned along geological fractures. These are buried under a sandy-gravely sediment cover with a thickness of several decimetres. The removal of this cover is essential to document the unique lithological structures beneath it. These are proving to have a complex sedimentary history and intense diagentical processes (Pohl et al., 2010; Stanulla et al., 2013; Stanulla et al., Pers. comm).

Fig 3: Excavation site in Panarea. Reservoirs, the counterweights and operating divers are all visible.

The mobile airlift pump is not a substitute for surface-supplied airlift dredging devices. It is rather designed for in-situ small-scale excavation of delicate objects or structures.

A combination of only a few parts and a slim design grants many benefits on mobility and transportability either above or under water. Under water, the airlift can be transported with standard lifting bags (50 kg). As there is no need for a surface supply, the divers are able to choose the most suitable deployment location, and are also unaffected by waves and surface currents. Since the apparatus is powered by compressed air only, there is no pollution by oil, fuel, combustion gas or aggregate noise. Furthermore, the used materials are carefully selected for environmental sustainability (e.g. high-density polyethylene (HDPE) tubings that are food safe).

Of course, the mobile design comes with some drawbacks: because the air supply is realised by standard scuba tanks, the working hours are limited. Our field tests were carried out in water depths of 22 m to 26 m, and by the time the reservoir ran out of air (ca. 30 min), we were close to decompression (Fig 6). Nevertheless, it is possible to change

Fig 4: Workflow of an airlift excavation: from a sandy burial to the sampling of unique small-scaled sedimentary structures. Location: Panarea, Italy (water depth = 21 m).

Fig 5: Before and after documentation of excavation sites in Panarea, Italy (water depth = 26 m). The diverse morphology of the volcanoclastic sedimentary rock would not be accessible without sediment removal. The investigations give insights in the genetical and diagenetical processes during sedimentation and hydrothermal alteration.

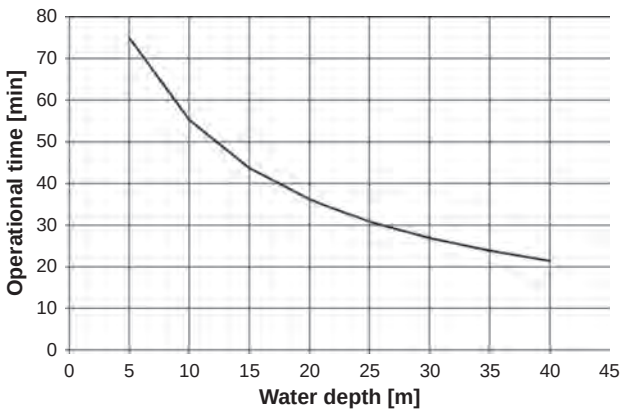

Fig 6: Empiric determination of the effective working hours of the mobile airlift pump (diameter riser pipe: 5 cm) at different water depths. Assumption: reservoir size of three 15 L standard scuba tanks with 200 bar.

Table 1: Advantages and disadvantages of the mobile airlift pump. This method is especially suitable for small-scaled structures demanding a mild removal of the sediment-cover.

Advantages	Disadvantages
Mobility	Limited operation hours
No need for a surface supply system	Limited suction power
Minimised influences of waves, currents	Optimised set-up is crucial
Environmental sustainability (e.g. no oil)	
Simple handling	
Low cost	
Transportation with normal lifting bags	
Mild removal of sediment cover possible	

these tanks underwater to extend this time. Preferably, 300 bar tanks should be used to prolong the operating time. As it is designed for the exposure of fragile objects beneath a sediment cover, the suction power is purposefully limited. If the sediment grains are comparatively coarse and elongated or disc-shaped, clogging might occur. This also happened when too much sediment was fed to the airlift pump without flushing the system by holding the suction hose into the water column for a few seconds. In most cases, the clogging could be fixed under water very quickly.

When there is no need for an unlimited supply of a high flow-rate, the mobile airlift pump is a real alternative with respect to low cost, high mobility, easy handling and cautious sediment removal (Table 1).

5. Conclusion

The calculation of effective working hours is based on experimental data gained during excavations at two different water depths (Fig 6). A varying mass-flow (air) was measured in different depths that represent the base for the consideration of a depth-dependent mass flow of air. The air consumption depends on a variety of different influencing parameters. Despite the water depth, the

design of the mixing chamber and the transported amount of sediment are crucial. The type of sediment also has a major impact. Furthermore, the air's volume changes non-linearly while rising. These facts influence the air consumption of the airlift. As a consequence, its gas-consumption curve has non-linear characteristics as one might expect due to the linear increase of ambient pressure. A distinct calculation would necessitate a complex mathematic calculation. The provided estimation instead gives orientation values for work and dive planning. Therefore, sufficient training and good experience of the working diver are necessary.

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doi:10.3723/ut.34.045 Underwater Technology, Vol. 34, No. 1, pp. 45–46, 2016 www.sut.org

Science of diving: concepts and applications

By Bruce Weinke

Published by CRC Press

Hardcover, 2015

ISBN: 978-1-498725-13-2

418 pages

Science is a systematic study of the structure and behaviour of the physical and natural world. As such, science encompasses a wide range of technical disciplines. However an initial brief inspection of this book will reveal that it is full of mathematical equations, derivations and numbers. The book's author, Bruce Weinke, is a scientist in the Applied Computational Physics Division of the Los Alamos National Laboratory in the US, his interest in physics and computing is reflected in the content of the book. In consequence, although it touches on some of the geosciences and medical aspects of diving, the book is not for readers without an interest in the mathematical aspects of science. On review, it is also clear that the book is intended as a reference text and not particularly suited for reading from cover to cover.

The book is split into five main sections: (1) 'Earth atmosphere, terrasphere and hydrosphere'; (2) 'Pressure, density and bubbles'; (3) 'Gas kinetics and phase transfer'; (4) 'Computing and diving algorithms'; and (5) 'Statistics, risk, comparative profiles and maladies'. Together with the main sections, there are annexes on 'Fundamental physical concepts' and 'Diveware and planning'.

A theme running through the book is the author's interest in decompression algorithms and calculation. He has produced a specific decompression computational algorithm known as reduced gradient bubble model (RGBM). While the text competently describes other algorithms that have been used, there is a tendency for the text to justify the benefits of bubble-based models and, specifically, RGBM. It may have been better as a textbook, and more independent, if the algorithm was considered on an equal basis to other decompression systems used. To its credit, the book does provide sufficient information and relevant equations, such that both enthusiasts and specialists may use it in support of their understanding and development of decompression procedures.

Although the book is intended to be on the 'Science of diving', it is very physical and mathematical in content, and so some of the topics covered seem to be very tenuously linked to diving. For example, some aspects covered in the first section are: 'Centrifugal and Coriolis effects'; 'Solar system'; 'Equinoctial precession and nutation'; and 'Epochal Panoramas'. Although these and many other sections are of a general scientific interest, they may not be particularly useful from a diving science perspective. How many diving scientists need to know about elementary particle interactions?

The book would not be considered as a general interest text, but it also does not fully fit with being an academic text. Instead, it bridges the gap between a traditional academic text and the requirements of an information-hungry recreational and technical diving community. It is provided with an extensive and comprehensive 16-page index, which I found useful and accurate in identifying particular topics and information of interest or to help cross-reference. It is also provided with nine pages of references, though unfortunately these were not linked to the text other than by the occasional authors name. Of concern for a textbook published in 2015, the only references I observed cited in the last decade were the authors own work.

Close to the front of the book, there is a short section on 'Conventions and Units' which has the following opening statements: *'Standard (SI) and English units are employed, By convention, by usage or for ease, some nonstandard units are employed'*. This unfortunately ends up as a confusing array of units and symbols with a heavy preference (as the author is US-based) for imperial units without conversion or link to the SI system. For ease of use, I would have preferred a consistent approach to units and preferably for the units to be SI. To assist the reader with comprehension of the topics being presented, at intervals throughout the book, there are 'Keyed Exercises' which give questions on the previous text together with the correct answer.

The book is in hardback with a glossy cover, 9.5" by 6.5" (240 mm by 160 mm), making it physically

simple to handle and read. It is well presented and is illustrated with black and white graphs and diagrams. It contains many equations and numerical tables to illustrate the principles being described; it may have been be easier for some readers to assimilate some of the presented principles if more had been presented as descriptive text.

The intended audience for the book is unclear; it seems to have been written for the scientific and technical diving communities. However, I would not consider it as a formal textbook nor a book that would be of interest to the majority involved in the scientific and technical diving community. It is not easy to read and I fear it is likely to spend more time on the bookshelf than being used for reference.

(Reviewed by Gavin Anthony, Consultant, Diving and Life Support Gosport)

Marine Bioenergy: trends and developments

Edited by Se-Kwon Kim and Choul-Gyun Lee

Published by CRC Press

Hardcover, 2015
ISBN 9781482222371

769 pages

The interest in producing bioenergy from either macro- or microalgae, especially in terms of the latter form of biomass, peaked at a time when the price of a barrel of oil hit new highs in the second half of the 2000s. The concept of using both forms of biomass for bioenergy is far from an new one: seaweeds in the form of kelps were investigated as a means of producing methane gas from in the 1970s; and the production of biodiesel was extensively investigated as part of the National Renewable Energy Laboratory (NREL) the U.S. Department of Energy's Aquatic Species Program – Biodiesel from Algae, which ran from 1978 to 1997. Although oil is still relatively cheap at the moment and many of the US-based start-up companies, whose initial focus was on biodiesel production from microalgae, have started to focus on other potential uses of the biomass, there is still interest in bioenergy produced from marine biomass. The book has the difficult task of conveying to a wide audience that this is still a relevant form of bioenergy.

Both editors have prior experience of producing books related to marine biotechnology topics, and the book is fairly extensive in its approach with seven individual sections. These cover the main types of bioenergy production, including the standard biodiesel from microalgae, to newer aspects of energy generation in the form of microbial fuel cells. It brings all this information together towards developing the idea of taking a more biorefinery approach to energy generation. There is a great deal of information contained within the ~730 pages of this book, and in general it is set out in a fairly logical manner.

A misleading aspect of the book is 'Section I: Introduction to Marine Bioenergy', which deals almost exclusively with energy production from microalgae and cyanobacteria. There is almost no mention of macroalgae or seaweeds. On just reading this, it might suggest that the book was just concerned with microalgae but this is not the case. The second section redresses the balance to a certain extent, but it might be difficult at times for the reader to tell that different chapters take slightly different approaches when discussing some of the same aspects of the technology (for example open ponds versus photobioreactors (PBR) cultivation).

The more interesting aspects of this area of science are presented in latter sections, particularly 'Section V: Bioelectricity and Microbial Fuels Cells' and 'Section VI: Marine Waste for Bioenergy'. Throughout the book, the chapters on the 'Current State of Research' are a strength and a weakness. They are potentially an invaluable resource in terms of reference material covering major aspects of marine bioenergy production and high value products. But these particular chapters have been presented in a slightly odd manner and do not tie all the information together. This seems like a missed opportunity, given the work that was obviously put into their production. The last section (VII), although covering commercialisation and global markets, would have benefited from a chapter tying everything together and maybe predicting where next for marine bioenergy, considering the push now for a biorefinery approach.

The book in general covers the major biotechnology and/or technology approaches to the production of bioenergy from marine biomass. It represents a good central reference source of information linked to marine bioenergy. However, there are flaws and the approaches now being taken that are more joined up in their approaches are not really reflected in the text.

(Reviewed by Dr Michele Stanley FRSB, Centre Lead for Marine Biotechnology Scottish Association for Marine Science)

Society for Underwater Technology

This multidisciplinary learned Society brings together individuals and organisations with a common interest in underwater technology, ocean science and offshore engineering. It is aimed at engineers, scientists, other professionals and students working in these areas. It was founded in 1966 with members in more than 40 countries and branches which have been established worldwide.

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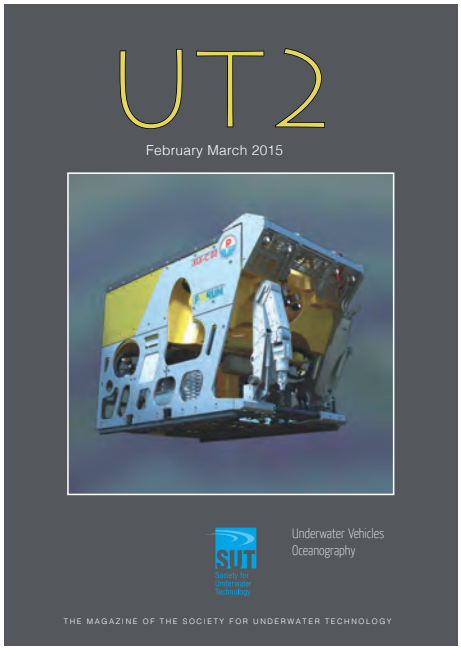

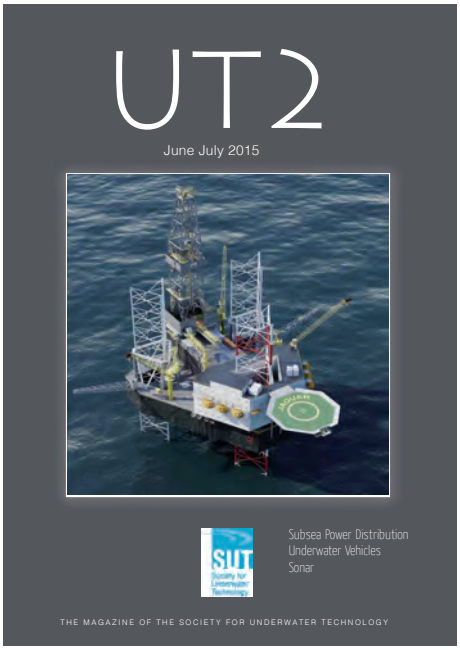

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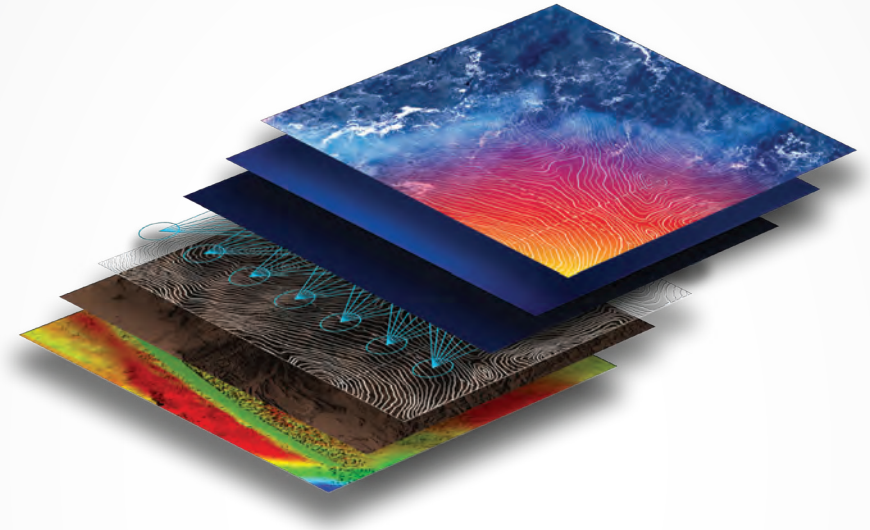

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