Archaeology:
Just Add Water

volume II

2019

UNIVERSITY OF WARSAW

ŚWIATOWIT Supplement Series U: Underwater Archaeology, vol. II

Financed by:
Polish Ministry of Science and Higher Education (959/P-DUN/2018)
Director of the Institute of Archaeology, University of Warsaw

Cover Photo: Humantay Lake, Peru 2016, by Przemysław A. Trześniowski
Back Cover Photo: Underwater Expedition IA UW at the 19th Archaeological Festival in Biskupin, Poland 2013, by Marcin Bartoszewicz

ISSN 2719-2997
ISBN 978-83-66210-03-5
Series DOI: 10.35538/uw.2719-2997
DOI of the volume: 10.35538/uw.2719-2997/978-83-66210-03-5

Typesetting and makeup: Aleksandra Chołuj, Małgorzata Mileszczyk, Magdalena Nowakowska
Print and binding: Elpil, Siedlce

„3rd Warsaw Seminar on Underwater Archaeology – zadanie finansowane w ramach umowy 959/P-DUN/2018 ze środków Ministra Nauki i Szkolnictwa Wyższego przeznaczonych na działalność upowszechniającą naukę”

Archaeology:
Just Add Water

Underwater Research at the University of Warsaw

Ministerstwo Nauki i Szkolnictwa Wyższego

United Nations Educational, Scientific and Cultural Organization

Unitwin Network for Underwater Archaeology

The Explorers Club — Polish Chapter — Oddział Polski

WARSZAWA 2019

Preface

Dear Colleagues,

It is our great pleasure to present to you the second volume of the U Supplement Series of the "Światowit" periodical. To a large extent it is based on the papers presented during the *3rd Warsaw Seminar on Underwater Archaeology*, which took place at the University of Warsaw on the 17th and 18th of January 2019.

An efficient and prompt process of editing we owe to the funding from the Ministry of Science and Higher Education, grant no. 959/P-DUN/2018.

Organization of the Seminar and publication of the hereby volume was possible thanks to the co-operation with the Polish Chapter of the Explorers Club, in particular its President, Professor Mariusz Ziółkowski, and the Vice-President, Marcin Jamkowski, to whom we are deeply grateful.

We would also like to acknowledge and appreciate the support of the University of Warsaw, namely the Vice-Rector Ph.D. habil. Maciej Duszczyk, the Dean of the Faculty of History, Ph.D. habil. Małgorzata Karpińska, Professor UW, as well as the Director's Board of the Institute of Archaeology: Ph.D. habil. Krzysztof Jakubiak, Ph.D. Michał Starski, and Ph.D. Marta Żuchowska.

The special thank you we traditionally owe to the Diving Museum by the Warsaw Diving Club, especially the Museum's Curator, Karina Kowalska, and the Club's President, D.Sc. Grzegorz Kowalski, who have been supporting our activities for many years, and constantly guide and help us in numerous enterprises.

We would like to extend our gratitude to all the Authors and Reviewers, who have been extremely diligent and punctual to keep up with our strict deadlines.

During the editing of the volume we have received invaluable consultations in the matter of ancient languages by Tomasz Płóciennik and Ph.D. Joanna Wegner, who we would also like to thank with all our hearts. The post-editing process was successful due to the the kind assistance of Ph.D. Rafał Dmowski, who we owe enormous gratitude.

The whole book was once again skilfully supervised and managed by the one and only irreplaceable Ph.D. habil. Bartosz Kontny, Professor UW. Him we would like to thank for all the advice and help with difficult choices, as well as the dedication to the organizational matters, even though the really tight schedule.

Last but not least, we would like to thank all the Readers who have reached for the hereby volume. We sincerely hope you will enjoy the outcome of our efforts and wish you pleasant reading!

Aleksandra Chołuj

Małgorzata Mileszczyk

Magdalena Nowakowska

3rd Warsaw Seminar on Underwater Archaeology

3rd Warsaw Seminar on Underwater Archaeology held on 17th-18th of January 2019
at the University of Warsaw
(photos by: M. Sugalska)

Foreword

The volume, which we hereby present to our esteemed Readers, is the vivid proof that underwater archaeology at the University of Warsaw is doing more than well. It is the second publication in the ***"Światowit" Supplement Series U: Underwater Archaeology***, issued for now (and we hope this pace will be sustained!) with a frequency of a periodical. Within the book one might find i.a. the texts being an outcome of the international ***3rd Warsaw Seminar on Underwater Archaeology***, organized in the Institute of Archaeology, University of Warsaw. The Readers will discover here the articles presenting broad chronological and geographical range of issues: from the Prehistory until the Second World War, from Guatemala and Peru to Poland and Slovakia. We are trying to reflect this diversified character also by the choice of photographs on the cover.

The leitmotif of all this vast range of archaeological issues is **water**: realm bearing a magnificent symbolic character. Changing its colour (even during the day – from the blackness, through greyness, then blue, until the bloody-red at the sunset, turning again into black) and visibility, it has manifested also other features, which can be contemplated as signs of its animation, such as movement: horizontal (currents, waves, tides) and vertical (fluctuations of the surface). It was also the source of life quite literally, providing food and dihydrogen monoxide, essential for living.

Along with its whole mystery and dangerousness, water may also serve as a refuge (lake settlements from the early Iron Age) and a trade route, at the end of which there is a (hopefully) safe harbour. That is how underwater archaeology marches onto the land... Although, it is neither place nor time for the deliberation about the definitions of archaeology related to water environment; the discussion in this matter has lasted for many years, abound in more and more new terminological propositions, still being far from any resolutions. Whichever position we assume in the aforementioned debate, it is impossible not to notice that the symbolism, the rituals, and everyday casual activities essential for life and connected with water pass through each other, which is well-exemplified by the hereby volume. Objects lost during transportation and other kinds of exploitation of water basins, items put in the water as a matter of rituals, military aspects connected with watery environment, lake settlements, harbours, and trade – all of that and even more you can discover in *Just Add Water 2*. To all the Readers, who are going to immerse themselves into this topic, I wish a pleasant intellectual adventure and... good dives!

Bartosz Kontny

DOI 10.35538/uw.2719-2997/978-83-66210-03-5.pp.93-113

Do not Mess with the Apus:
Technical and Safety Aspects of the High Mountain Underwater Archaeology

Przemysław Adrian Trześniowski*

Abstract:

Since the 1960s underwater archaeology has developed into a thriving and well-established branch of archaeology. Some of its areas, such as underwater research conducted at very large depths or in inundated, hardly accessible caves, are still poorly researched, and such studies push the borders of our knowledge concerning not only the past of the human kind, but also what is known about our planet. Underwater archaeologists either dive themselves or use remotely operated vehicles to reach the places where no human being had been before them. This is why the reference materials on both sub-disciplines are so scarce. Exactly the same situation is observed in case of high-altitude underwater archaeology.

Searching for traces of any human activity in high mountain environment requires a state-of-the-art and innovative equipment, and also a pioneering approach to conducting research in extreme conditions. At an altitude of over 4 000 m a.s.l. underwater archaeological research has been conducted so far only in Sun Lake (Lago del Sol) and Moon Lake (Lago de la Luna) located in the crater of the Nevado de Toluca volcano, Mexico. Much more is known about Lake Titicaca (3 809 m a.s.l.; Bolivia and Peru), located at slightly lower altitude, due to a large number of expeditions, be it scientific or not. In 2016 and 2017 two seasons of underwater research were organised in the Machu Picchu region (Peru) in the lakes located at altitudes between 4 130 and 4 531 m a.s.l. In underwater research in such extreme conditions scientists had to use specially designed dive tables and diving equipment; they have also developed innovative strategy for their application. Emergency procedures for diving in a location far away from any roads and the GSM network needed to be implemented as well.

Keywords:

high mountain underwater archaeology, high altitude diving, diving equipment

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Nevado Salkantay (Peru) – Introduction

Towering over the Machu Picchu National Park (*Santuario histórico de Machu Picchu*, Peru), Salkantay (6 271 m a.s.l.) is the highest mountain in the Vilcabamba range (Cordillera de Vilcabamba) in the Peruvian Andes. As such, Salkantay is the axis of the sacred landscape of the Machu Picchu area, and *Apu*[1] *Salkantay* associated with the mountain is the strongest local deity in the region. It is surrounded by a network of ancient roads that used to be the arteries of the former Inca Empire. Some of these roads lead close to high mountain lakes, which, basing on accounts from the chronicles from the period after the Conquest, such as Felipe Guaman Poma de Ayala (*Nueva corónica y buen gobierno...*, after: Adorno [ed.] 2001: 263–267, 273), Pedro de Cieza de León (*Crónica Del Perú...*, after: Pease [ed.] 2005: 225, 261–262), Francisco de Avila (*Dioses y Hombres de Huarochirí...,* after: Arguedas [trad.] 1966: 72, 89–92, 95–98), or Inca Garcilaso de la Vega (*Comentarios...*, after: Herrera Villagra [ed.] 2018: 34–35, 66, 110, 123) could represent *huacas*[2], specific nodes in the network of *ceques*[3], invisible lines extending from Cuzco through the sacred Inca landscape (Szemiński and Ziółkowski 2014: 105–110, 421). These lakes became the subject of interest of the researchers from the Centre for Precolumbian Studies, University of Warsaw (hereinafter: OBP[4]) who in 2016–2017 in cooperation with the Peruvian Ministry of Culture[5], examined five of them as part of the project *The Function of Satellite Sites in the Machu Picchu Region: the Inkaraqay and Chachabamba Sites and High Mountain Lakes in Nevado Salkantay (Peru)* led by Professor Mariusz Ziółkowski[6] (Sobczyk *et al.*, forthcoming).

Lakes: Humantay (4 270 m a.s.l./20 m depth; **Fig. 1**), Inka Chiriaska (4 735 m a.s.l./29 m depth), Salkantay Verde (4 460 m a.s.l./25 m depth), Soqtaqocha (4 531 m a.s.l/18 m depth; **Fig. 2**) and Yanaqocha (4 130 m a.s.l./5 m depth; **Fig. 3**), all Nevado Salkantay, Peru and several smaller pools were researched by means of a hydroacoustic equipment[7] in order to collect

[1] Title of the living mountains, the greater gods (Szemiński and Ziółkowski 2014: 448). Mythical ancestors that protect the people living in their vicinity. *Apus* also identify ethnically the territories occupied and attached to these peoples (Herrera Villagra 2018: 370).
[2] Local deity, oracle, sanctuary, temple ruins, one but in two parts, a pair of the ancestor-founders who sprouted from the earth (Szemiński and Ziółkowski 2014: 448). The *huacas* could be trees, rivers, lagoons, caverns, rocks, mountains, or natural places where the ancestors rest (Herrera Villagra 2018: 370).
[3] Zigzag, a procession route coming out of the main temple in Cusco and visiting various places of sacrifice – – *huacas* in turn (Szemiński and Ziółkowski 2014: 450).
[4] Polish: *Ośrodek Badań Prekolumbijskich, Uniwersytet Warszawski*.
[5] Spanish: *Ministerio de Cultura del Perú*.
[6] The research was funded by the *Dirección Desconcentrada de Cultura – Cusco, Ministerio de Cultura del Perú* (*sucursal regional en Cusco del Ministerio de Cultura del Perú*), Polish Ministry of Science and Higher Education (grant nr 4815/E 343/SPUB/2014/1) and Polish National Science Centre, Poland (grant No. UMO-2015/19/B/HS3/03557) as a part of the OPUS 10 call.
[7] Lowrance Echo Sounder HDS-12 Gen 3 ROW with the 83/200 kHz converter and Sonar StructureScan.

data for subsequent bathymetric maps and to select bodies of water for further underwater research. Due to the lack of visible traces of human activity in the pre-Columbian period lakes Inka Chiriaska and Salkantay Verde were excluded from them (Sobczyk *et al.* 2016; Sobczyk *et al.* 2017; Sobczyk *et al.*, forthcoming).

Although located at a similar altitude as Sun Lake (Lago del Sol) and Moon Lake (Lago de la Luna) in Nevado de Toluca (Mexico), the Andean lakes in the Machu Picchu National Park differ significantly from those in the Toluca volcano crater in terms of logistics.

While access to Humantay Lake takes only two hours of climbing from Soraypampa (3 908 m a.s.l.), the nearby guard station of the National Park Machu Picchu, where diving equipment can be still delivered by car, Soqtaqocha Lake (Laguna de Soqtaqocha) and Yanaqocha Lake (Laguna Yanaqocha), both Nevado Salkantay are far away from the last place accessible by car. Then the whole expedition equipment must be carried on the mules (**Fig. 4**) and shouldersof participants and it takes two full days of hiking to cover the long distance. A part of the route to the Soqtaqocha and Yanaqocha lakes leads through area of the wild nature. The last section is so harsh that even the mules cannot be used for transportation. This has a considerable impact on the quantity and weight of the expedition equipment. Consequently, the emergency procedures in the event of a diving accident in a place far beyond the access of the GSM network and far, far away from any communication routes need to be adjusted. An additional difficulty for the expedition is the lack of any diving industry infrastructure in the Cuzco area of Peru.

High Altitude Diving – Planning and Preparation

High altitude diving and high altitude underwater research require precise planning, including the logistics of trekking to the lakes and return to the camps. In terms of human physiology, diving at high altitudes does not begin when one submerges, nor does it end when one surfaces. Changes in altitude and atmospheric pressure before and after diving affect the body, specifically the process of saturating and de-saturating tissues from inert gases. Along with changes in altitude the repetitive groups widely known from the dive tables change. If the dive would be made immediately following trekking from sea level to altitude, the diver would carry in his tissues the nitrogen from the sea level and much longer decompression would be required. Upon ascent to altitude the body off-gases excess nitrogen to come into equilibrium with the lower partial pressure of nitrogen in the ambient environment. It also begins acclimatization to the lower partial pressure of oxygen. About twelve to over twenty four hours is required for full equilibration, but acclimatization takes much longer. The risk of contracting DCS[8] increases during the ascent to further altitude after diving, because of the rise in the nitrogen gradient between the body and the environment. Therefore, the planning of high altitude dives should not include only profiles of the dives themselves according to a dedicated algorithm or specially prepared tables for this purpose; in the planning of underwater research, both the time of acclimatization at an altitude close to the researched lake and the elevation differences between the surface of the reservoir and the camp, as well as the profile of the route linking the place where the research is carried to the camping place should always be taken into account (**Fig. 5**). The key safety factor during the diving itself is a specially limited ascent rate not only because of DCS risk, but also due to the hazard of fast exposure to hypoxia[9]. The safety and decompression stops, as well as the maximum operating depths for individual gases, are also shifted to the different depths. The safety stop and the surface interval must be significantly extended (Böni *et al.* 1976: 190–193; Bühlmann 1989; Egi and Brubakk 1995: 295; Kot 2016:1–6; Hennesy 1976: 40; Paulev and Zubieta-Calleja 2007; U. S. Navy 2016: 9-46–9-58; Wienke 1993). However, the exact explanation of these principles is not the purpose of this study.

There were plenty of solutions proposed for the safe high altitude diving since the Cross corrections were published for the first time in 1967.[10] Cross tables have not accounted for the difference in density between fresh and salty water, so Bell and Borgwardt (1976) created a new algorithm, dive tables, adjusted the ascent rates, depths, and lengths of decompression stops. Hennesy (1977) proposed new formulas for converting standard air decompression tables for no-stop diving at altitude. His predictions were more or less in agreement with the later Bühlmann's tables (1984). Two cases of paraplegia registered after a dive of Swiss Army divers at altitude of 1 800 m a.s.l. in 1969 gave the motivation for experimental work on dive algorithms and dive tables with reduced ambient pressure in Switzerland (Bühlmann 1989: 412). So, Böni, Schibli, Nussberger, and Bühlmann (1976) have developed CRE[11] algorithm and dive tables up to 3 200 m a.s.l. with an obligatory decompression stop at the depth of 2 m, but they were

[8] Decompression Sickness.
[9] Condition in which the body is deprived of adequate oxygen supply at the tissue level, may lead to unconsciousness without symptoms.
[10] The Cross corrections (CRT – constant ratio translation) use the ratio of atmospheric pressure at the relevant altitude to the pressure at sea level to calculate an equivalent sea level depth that represents the same relative pressure changes (*cf.* Cross 1967: 60; Cross 1970: 17–18, 59; both after: Bell and Borgwardt 1976; Basset 1982: 7; Egi and Brubakk 1995: 285–286, 294; Hennessy 1977: 39–41; Paulev and Zubieta-Calleja 2007: 214).
[11] Constant ratio extrapolation.

tested only up to 2 000 m a.s.l. in the Alps. Albert A. Bühlmann (1989) worked out ZHL-16 dive algorithm based partially on the data from the real 290 dives in Lake Titicaca (3 809 m a.s.l.; Bolivia and Peru). Egi and Brubakk (1995: 283) observed that existing algorithms did not take into account a possible change in the gas equations or DCS boundary[12] due to the hypoxic response of the diver body above 2 400 m a.s.l. They postulated the possibility of taking into account the length of acclimatization at a given altitude (Brubakk 1995: 295). Poul-Erik Paulev and Gustavo Zubieta-Calleja, Jr. (2007) proposed a standardized equivalent sea depth (SESD), a new conversion factor, but their simplified approach was addressed for recreational divers and was not tested before publication. So, when the NASA Astrobiology Institute mounted an expedition to the crater lake of the volcano Licancabur (5 913 m a.s.l., Bolivia) in November 2006, stating the absence of tested dive tables giving safe decompression and ascent rate limits for diving above 4 267 m a.s.l., NASA Diving Safety Office has extrapolated its own tables (Morris *et al.* 2007: 157). In order to plan underwater research in the Machu Picchu region, in the Peruvian Andes, The OBP has established cooperation with the National Centre for Hyperbaric Medicine[13] in Gdynia (hereinafter: KOMH). For the purposes of the project, Ph.D. habil. Jacek Kot, M.D. from KOMH has developed algorithms and dive tables taking into account the Cross corrections for US Navy air tables, with the adjusted depths and durations of decompression and safety stops and the principles of planning and implementation of safe diving and logistics for the altitudes at which the project activities were planned, such as i.e.: maximum ascent rate during a dive, minimum time of acclimatization at the altitude before a dive, maximum altitude difference after a dive, minimum surface interval etc. (Kot 2016: 1–6). All diving activities in the 2016 and 2017 research seasons were planned and implemented in accordance to these recommendations. According to KOMH's recommendations (Kot 2016: 7) the team also included a qualified diving rescue instructor of Divers Alert Network (DAN) with specializations, *i.a.* Advanced Oxygen Provider, Dive Medicine for Divers, and Neurotic Assessment On-Site at the instructor level. As part of the diving in the Alpine lakes in the area of Machu Picchu a collection of data on micro-bubbles formed in the human body by the Doppler meter, used for the purposes of the project by KOMH, was planned as well.

[12] Equivalent of M-value but measured in absolute ambient pressure not gauge ambient pressure.
[13] Polish: *Krajowy Ośrodek Medycyny Hiperbarycznej.*

Diving Equipment and Configuration

Tanks, Gases, Harness...

One of the main risks associated with the equipment when diving in cold water, especially at the high altitudes, where sudden and uncontrolled surfacing is far more dangerous than at the sea level, is the risk of the regulator's free-flow. For high altitude diving in the lakes around Nevado Salkantay the sidemount configuration has been chosen (**Fig. 6**), which, unlike back-mounted cylinders, enables reaching the proper cylinder valve immediately in the event of failure of any of the regulators. The sidemount configuration allows for the independent exploration diving. The sidemount has been proven in numerous exploration projects in the most demanding underwater environment, also an overhead one. The sidemount configuration provides full independence and continuity of diving in accordance with the safety rules even in the event of free-flow or other diving regulator failure.[14] Also it makes possible the convenient implementation of multi-gas diving with accelerated decompression included.[15] Due to the serious risk of DCS after a too fast ascent during high altitude diving, the sidemount configuration is recommended even for single-cylinder diving.[16] It then gives the diver an option of controlled opening and closing the cylinder valve only for the purpose of taking another breath, during an emergency ascent with safe speed after the failure of the diving regulator.

The gas recommended for diving in the lakes around Nevado Salkantay was EAN 40[17] (Kot 2016: 2), which maximum operational depth (hereinafter: MOD) does not exceed the maximum depth of any of them. Unfortunately, due to the lack of diving infrastructure in the Cuzco area, this gas could not be obtained. At the disposal of the participants of the expedition in 2016, however,was air and oxygen but the maximum pressure in the cylinders that was possible to obtain in Cuzco did not exceed 160 bar. As the result, the modification of the gas management algorithm for the sidemount was implemented, using air in the primary

[14] The safety procedure in overhead/technical diving with the sidemount configuration in an event of damage to one of the diving regulators and as a result of free-flow consists in, if possible, breathing from the same cylinder with a defective diving regulator first in order to maximize the use of the breathing gas and keeping a safety gas reserve in the other one. For this purpose, the cylinder with the defective diving regulator is opened and closed every time only for the diver to take a breath.

[15] In case when there are two different gases in each of the sidemount cylinders (oxygen and air) and the free--flow malfunction of air cylinder happens at the depth at which oxygen cannot be used due to a risk of oxygen toxicity, only the tank with the air can be used at this moment until a safety depth for breathing with oxygen is reached by a diver; a safe ascent rate needs to be maintained as well. In this case going up to the surface as fast as possible is not an option due to the serious risk of DCS. In case of a free-flow of the diving regulator attached to the oxygen cylinder one can always breathe the air from the other tank at the same depth.

[16] The safety procedure with the cylinder valve opening and closing mentioned before, especially in the case of a single diving cylinder placed on the back of a diver, seems to be at least inconvenient; therefore, there are other safety procedures to be used in the case of free flow in the backmount configuration.

[17] MOD for EAN 40 PO_2 1.4 ata at the altitude 5000 m a.s.l. is 29.7 m (Kot 2016: 2, 5).

tank, because in the event of a failure it was possible to breathe at any depth, which in the researched lakes did not exceed 30 m and medical oxygen in the secondary tank.[18] In this case, oxygen is recommended for breathing during the safety stop and possible decompression stops (Kot 2016: 2), providing additional protection in the event of DCS or AGE[19]. Additionally, the oxygen used from its MOD during an ascent phase of a dive should prevent a diver from the fast exposure for hypoxic ambient pressure during the last metres of ascent – the phenomenon clearly felt during an ascent in case of breathing air.[20]

Due to the lack of any diving infrastructure in the Cuzco area all diving cylinders for the purpose of research were transported from Poland. In 2017 the situation became even more difficult due to the failure of the air compressor in Cuzco. Diving in the lakes Yanaqocha and Soqtaqocha, was limited to the underwater survey of the coastal line to a depth of 8 m. The dives could be made with the use of pure oxygen. Thanks to the fact that there was the air in one of the tanks which remained from the previous year, diving was also carried to the bottom (20 m) of Humantay Lake to finally close the underwater survey of this reservoir.

A proper acclimatization protects the expedition team from AMS[21]; however, with longer stay at the high altitudes some degree of hypoxia could always be a problem as its effects pose a serious danger that increases with altitude (Egi and Brubakk 1995: 292, Morris *et al.* 2007: 157–159). In 2019 the expedition team had at his disposal an air compressor, but basing on the experience of two previous field seasons, to avoid a risk of problems caused by the decline in physical and mental performance, it has been set that divers should breath pure oxygen during all dives shallower than its $MOD^{1{,}4\,ata}$.

Weights – the Heavy Problem

The problem of diving weights in the Andes is primarily a logistics problem. Transporting extra weight requires the involvement of more mules, which entails additional costs for the expedition. What is more, no lead could be found near Cuzco so the project had only a few kilograms of diving weights to use. The missing weights were replaced with shopping bags filled with rocks collected on the shores of the lakes (**Fig. 3**). However, this is notan ideal solution due to the fact that the density of stones is lower than that of lead such weights take much more space. They can also dynamically change the centre of balanceof the diver, thus having a negative impact on his safety. The location of the ballast

[18] MOD for O_2 PO_2 1.4 ata at the altitude 5000 m a.s.l. is 8.7 m (Kot 2016: 2, 5).
[19] Arterial Gas Embolism.
[20] NASA Astrobiology Institute High Lakes Project due to safety reasons used oxygen for all dives in the Licancabur volcano crater (5 913 m a.s.l.; Bolivia) however its depth is no more than 4.8 m (Morris et al. 2007: 157–158).
[21] Acute mountain sickness.

under the body of the diver also causes trouble when undertaking any underwater activities that require manual work or swimming close to the bottom. Based on the experience of the past two seasons it is necessary to supplement the equipment with specially prepared casesfor rocks or gravel, which could be e.g. fastened on the back or to the diving cylinders.

How to Measure a Real Depth at an Altitude?

Information about the depth and time of diving is one of the basic factors that allows for the implementation of a safe dive, consistent with the previously planned profile. As the measuring equipment used for diving is usually calibrated for the sea-level, depth information provided by dive computers and other digital measuring devices in high mountain conditions may be seriously misleading (**Fig. 7, Fig. 8**). This is why high altitude underwater survey requires consideration of this problem and specific diving equipment preparation.

Due to the specific high mountain conditions – low atmospheric pressure, influencing the depth readings of the analogue submersible pressure gauges (SPG) and diving computers (Mackay 1976: 400–401, U. S. Navy 2016: 9–49), the depth line rulers were constructed in the form of a marked line reeled on wide spools made from PVC pipes, facilitating handling them in dry gloves (**Fig. 8**). The capillary gauges – the devices that implement Boyle–Mariotte's law – could be used for a safe high altitude diving in combination with the sea level dive tables as well (Mackay 1976: 401, Egi and Brubakk 1995: 286); however, the capillary gauges do not show true depth values at high altitudes, so they could not be simultaneously used for documentation purposes. The literature mentions some dive computers adapted for high altitude diving (Bühlmann 1989 :411,420, Egi and Brubakk 1995: 285–286, 290, 293–294) of which those based on Bühlmann's algorithms looked particularly interesting.[22] However, the manufacturers of the technical dive computers that the expedition team had at their disposal did not guarantee that these would work properly at the indicated heights and, as Buzzacot and Ruehle (2009) have shown, even computers certified by manufacturers for diving at altitudes like 4 000 – 6 000 m a.s.l. are no longer reliable at 3 000 m a.s.l. when it comes to the depth readings, so testing dive computers in the field conditions could only become a side thread of the expedition. An additional factor were safety issues – the need to constantly mark the position of the diver and,

[22] Work of Albert A. Bühlmann (1989) was based partially on the data from the real 290 dives in Lake Titicaca (3 809 m a.s.l.; Bolivia and Peru) gathered in 1987 and 254 dives accomplished in Switzerland at little lower altitudes of 1 000–2 600 m a.s.l. ZH-L16 algorithm was designed for the altitude diving; as an additional safety factor it assumes that the diver is fully saturated with sea level nitrogen regardless of the time spent at altitude (Bühlmann 1989, Egi and Brubakk 1995: 294, Egi *et al.* 2003: 233).

if so, the possibility of pulling the diver up to the surface. So, the depth line rulers were connected with surface buoy markers made of two empty bottles with a total displacement of 9 l. Additionally, due to safety reasons, the spools of depth line rulers and consequently surface buoy markers connected to them were attached to the diver's harness during a dive, enabling reaching the diver in case of serious problems, such as loss of consciousness underwater, etc. Because the environmental conditions, such as visibility or water temperature prevailing in the Andean lakes in the Machu Picchu area, had not been known before a bright yellow line was chosen as it is better visible in the water with thick suspension or sediment rising from the lacustrine bottom.

Different Methods of Marking the Lines for a Depth or Distance Measurements

The standard method of marking a line that serves as a tool for measuring distance or depth in water is a previously prepared rope with knots tied on it, the so-called knotted line (knots at a distance of three feet) or 'rop-y-dop' (knots at a distance of a foot). The first tool allows e.g. for total measurement of the length of the cave corridors/sizes of the reservoir (the knots are counted on the way back, after the reel is fully extended or the end of the corridor is reached). The second tool is usually three feet long and is used for more detailed measurements. Knotted line, however, does not allow determining the distance to the end/beginning of the rope in any place, unless the count of knots is kept in mind. It is therefore not suitable for efficient depth measurement during high mountain dives.

For shorter distances, up to several dozen meters, there are other solutions, allowing for safe laying of the rope on a spool or reel, as presented in the figure (**Fig. 9**), bar code # M1. Marking a rope with a bar every five metres is too imprecise for the needs of high altitude underwater archaeology, where the exact measurement of depth is a key issue for security.

In contrast to the # M1 bar code, where a bright line is marked every five metres with black bars each marking a further five metres of the rope length, a lines of depth line rulers, built for the purposes of the project were marked with an insulating tape every one meter with the maximally different colours: red and blue (**Fig. 10**).

Each blue bar denotes a depth of one metre (in the range of one to four metres), each red bar means five metres depth. For depth reading, the value of bars in a given part of the line needs to be added. It is similar to Maya arithmetic, based on vigesimal positional numeral system which was, however, additive on particular positions, in a range 0–19. Because already the depth of eight metres water column blocks the red colour, making both colours look almost the same, the team has additionally adopted the principle according to which the red stripes should be found underneath the blue stripes. The length of the string on the spool was 20 m, as it has been assumed that the dives in the 2016 and 2017 seasons should not have been deeper than 20 m.

In practice in the 2016 season no dives were deeper than eight metres. It was decided to make the most of the available time and limited resources (tanks) in order to survey the coastal zone of Humantay Lake (**Fig. 1**). In this area, the applied bar code worked perfectly well. In 2017 the very bottom of the Humantay Lake was surveyed as well (**Fig. 11**) and it occurred to be 20 metres deep that season. In this way the reliability of technical diving computers in the full range of depth for which diving can be carried in subsequent research seasons was also checked. None of the lakes in which further underwater archaeological research is to be performed exceeds 20 m of depth.

<u>*Summary*</u>

High mountain underwater archaeology opens new horizons, allowing researchers to reach places not previously surveyed by archaeologists. The implementation of underwater research in the extreme conditions in the Andes requires thorough physical and equipment preparation, proper acclimatization and precise route planning as well as precise diving planning. The biggest challenge for the human body is the effort associated with the need to reach the researched reservoirs and the reaction to long-term stay in high mountain conditions. The human body is influenced by such factors as: low air pressure with hypoxic partial pressure of oxygen (**Fig. 5**), very low air humidity and low temperatures, often going down well below zero at night. As shown by the results of the research in the regions of Nevado Salkantay (Sobczyk *et al*., forthcoming), Nevado de Toluca (Luna *et al.* [eds] 2009) or Lake Titicaca on the Peruvian and Bolivian border (Reinhard 1992; Delaere 2017) it is worth the effort.

Diving in low temperatures requires earlier preparation for work in a drysuit, and in particular with dry gloves due to the fact that the researchers of the Sun Lake and Moon Lake complained about the problem of low temperature of water and its impact on manual motoric skills during prolonged exposures (Junco 2009: 24). However, as it can be seen in their pictures, they probably did not use dry gloves. For a drysuit diving in these conditions, an appropriate undersuit should be used that can absorb a large amount of water, isolating it from the body of the diver in the event of failure and flooding of the drysuit. It is also worth considering electric heating with heated gloves as well.

High altitude diving requires special algorithms that change the acceptable ascent rate, depth, and duration of the decompression stops as well as that of a safety stop, while the logistics and planning of diving must include equilibration and acclimatization at a given altitude, trekking between the camps and the lakes taking into account the maximum elevation on the route and very long surface intervals after each dive. According to safety rules researchers should plan no more than one dive per day. Maximum operational depths (MOD) for particular gas mixes are also very different than at the sea level (Kot 2016:2, 5). KOMH rules and recommendations worked well for the Andean expedition thorough three field seasons in high mountain conditions, but how does high altitude affect the risk of DCS, especially after the longer time spent in the high mountains, and how diving affect the risk of AMS is still not known because of the absence of the wider research (Egi *et al.* 2003: 233; Morris *et al.* 2007:158). Egi and Brubakk (1995: 295) warned against high altitude diving after full acclimatization (10 days higher than 3 000 m a.s.l.) until controlled experiments will be carried about the DCS stress induced by subclinical development of HAPE[23] on the other site performing in the high mountain conditions requires longer acclimatization from the sojourners, so special precautions are always required.

In the case of research realized in the lakes located far from any roads, the weight of expedition equipment becomes quite a considerable problem. Due to these limitations, it seems quite important to design stable diving weight pockets for loose materials or stones. Research undertaken in areas located far from communication routes and the GSM network also implies the need to develop emergency procedures in case of diving accidents. Satellite or radio communications as well as adequate supplies of oxygen are a necessity in such a case.

Comparative depth measurements carried by means of various devices yield interesting results (**Fig. 7, Fig. 8, Fig. 11**). It has been proven that technical diving computers taking into account the value of atmospheric pressure on the surface of the water perform well with the measurement of depth underwater at high altitudes. However, this should not change the safety procedures involving the use of a spool permanently attached to the diver's harness and connected with the surface buoy marker, in case of serious problems, such as unconsciousness underwater. The most flexible and safe diving equipment configuration for high altitude diving appears to be sidemount configuration with possible modifications to the gas management algorithm: use of the air in one sidemount cylinder for a deeper part of a dive and the oxygen in the other one for a shallower part to protect a diver from the risk of exposure to hypoxic environment conditions when performing tasks underwater, as the high altitude diving is physically demanding and requires a full readiness and consciousness for safety.

[23] High altitude pulmonary edema.

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Fig. 1 – Humantay Lake (4 270 m a.s.l./20 m depth) at the feet of Humantay glacier (5473 m a.s.l.) in Nevado Salkantay, Andes, Peru (photo by: P.A. Trześniowski 2016)

Fig. 2 – Soqtaqocha Lake (4 531 m a.s.l./18 m depth) in Nevado Salkantay, Andes, Peru (photo by: P.A. Trześniowski 2017)

Fig. 3 – Yanacocha Lake (4 130 m a.s.l.; Nevado Salkantay, Peru), an improvised diving weights pocket made of materials available on the spot in Peru – a cumbersome and hardly safe solution (photo by: P.A. Trześniowski 2017)

Fig. 4 – Mules, the true heroes of every Andean expedition (photo by: P.A. Trześniowski 2017)

Fig. 5 – Taking the altitude, temperature and the oxygen partial pressure measurements. The red alert values on the screen of technical dive computer shows that oxygen partial pressure at the altitude of planned underwater research is hypoxic. Without proper acclimatization, this partial pressure of oxygen in the surrounding atmosphere could cause fainting. Therefore, in high altitude underwater archaeology, the planning of acclimatization is so important, both before the expedition and before working on particular sites at different altitudes (photo by: P.A. Trześniowski 2017)

Fig. 6 – Diving equipment used for high altitude underwater archaeology. On the left an analogue depth gauge made of water tanks and a reel with a marked line, in the centre a diver in the sidemount harness with the primary tank at the side where the air is located (in the Nevado Salkantay lakes you can always breath with air), on the right a prepared secondary tank with oxygen − MOD for PO_2 1.4 ata in the lakes researched by the project is 8.7 m (photo by: M. Sobczyk 2016)

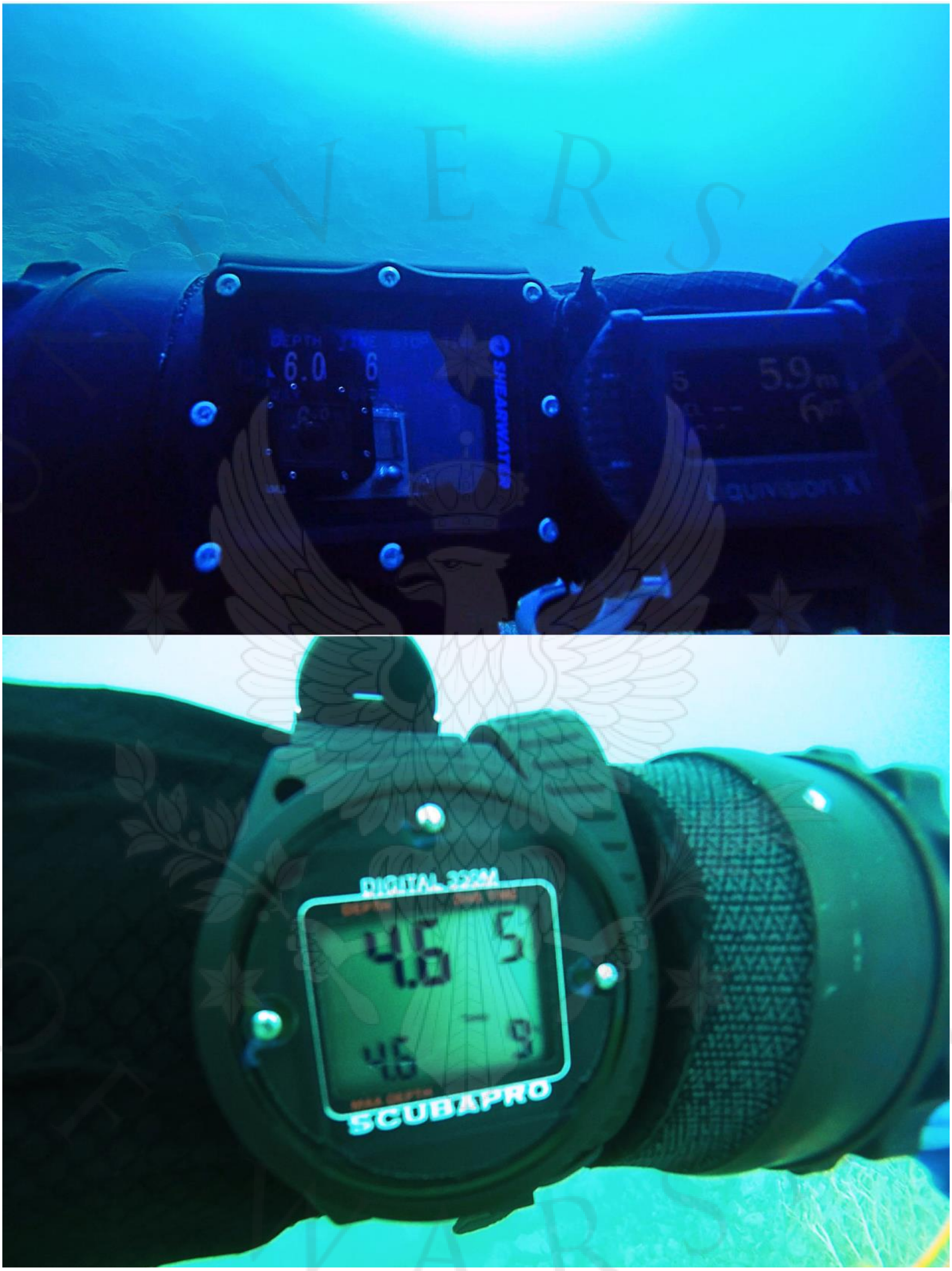

Fig. 7 – Comparative measurement of a depth of 6 m in Humantay Lake using various devices.
At the top the technical dive computers Shearwater Perdix and Liquivision X1, at the bottom Scubapro Digital at the same depth (photo by: P.A. Trześniowski 2016)

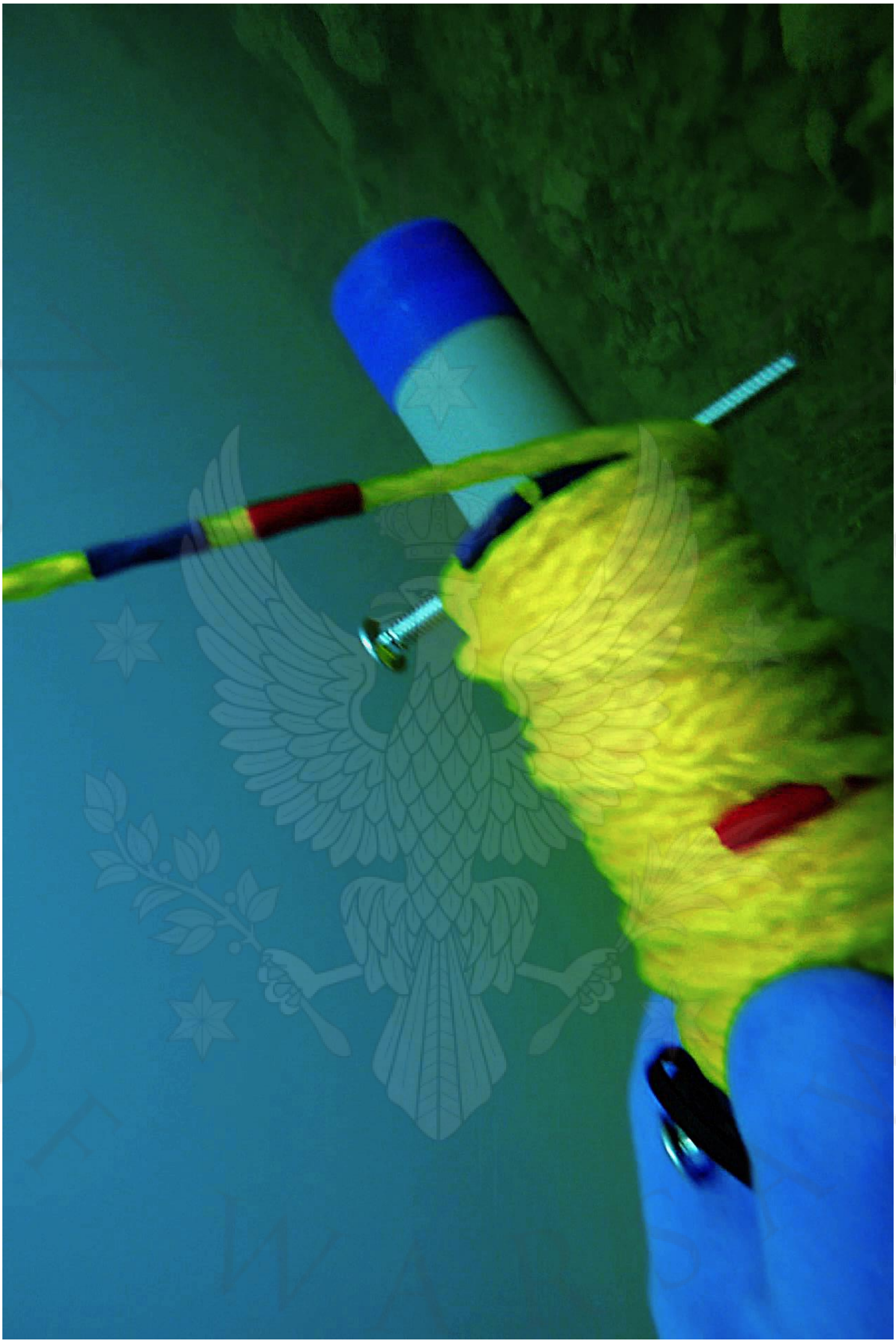

Fig. 8 – Comparative measurement of a depth of 6 m in Humantay Lake using an analogue depth gauge: an improvised spool with unsinkable line marked with # M2 bar code.
In the picture, a depth of Σ 5 m x (red stripes) + 1 m x (blue stripes) = 6 m
(photo by: P.A. Trześniowski 2016)

Barcode	Depth in meters
	5
	10
	15
	20
	25

Fig. 9 – Bar code #M1 for measuring the depth or distance on the diving reel or spool (elaborated by P.A. Trześniowski)

Barcode	Depth in meters
	1
	2
	3
	4
	5
	6
	7
	8
	9
	10
	11
	12

Fig. 10 – Bar code #M2 for measuring the depth or distance on the diving reel or spool (elaborated by P.A. Trześniowski)

Fig. 11 – Comparative measurement of a depth of 20 m at the bottom of Humantay Lake using technical diving computers that take into account the value of atmospheric pressure. An example of a voltage drop in the computer's battery on the left due to the ambient temperature is one of the problems to be taken into account when planning high altitude underwater expeditions
(photo by: P.A. Trześniowski 2017)

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ISBN: 978-83-66210-03-5