PAPER

HADEEP: Free-Falling Landers to the Deepest Places on Earth

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ABSTRACT

The hadal zone, comprising mostly deep trenches that plummet to nearly 11 km deep, represents the largest poorly understood habitat on Earth. This knowledge dearth has been technology induced rather than of scientific interest. The U.K.–Japan collaborative project Hadal Environment and Educational Program (HADEEP) is one venture where scientists and technologists have been working to fill this knowledge gap, particularly from a biological perspective. With limited funds and even more limited time, two 12,000-m autonomous free-fall baited imaging landers, known as hadal landers, were constructed to follow in the footsteps of the 1960 *Trieste I* dive; "to remotely go where two guys had gone before." In the past 2 years, the hadal landers have been deployed in five hadal trenches in the North and South Pacific Ocean across a depth range of 5,500–10,000 m. This new technology has led to many new discoveries including, among others, large aggregations of fish at 7,703 m, which are the deepest video footage of fish ever taken. Here we describe the origins of the HADEEP project, the challenges in developing the technology, and the scientific outcomes of exploring the deepest environment on Earth some 50 years after the pioneering *Trieste I* dive to Challenger Deep.

Keywords: Hadal zone, Trenches, Free-fall baited landers, Deep-sea technology

Introduction

The hadal zone (6,000–11,000 m) is a geographically disjunct deep-sea environment comprised mostly of deep trenches formed by tectonic subduction (Stern, 2002). Hadal trenches account for the deepest 45% of the oceanic depth range and host active and diverse biological communities (Beliaev, 1989). The first major trench sampling campaigns were conducted during the early 1950s on the Danish *Galathea* and Russian *Vitjaz* expeditions. Using trawl and grab methods, the diversity, abundance, and biomass of invertebrates were described and showed a seemingly high degree of endemism. Since then, very few trench sampling campaigns, particularly at an intertrench level, have been undertaken and as a result ecological information is sparse. All reviews of the hadal environment (Wolff, 1960, 1970; Angel, 1982) have primarily been based on the two 1950s data sets; therefore, ecological interpretation of hadal trench ecosystems is not comprehensive and is at best speculative. Considering all trenches to be a single habitat is likely to confuse interpretation of environmental drivers. Intertrench ecosystems are likely to be determined by the interaction of, for example, the geography, hydrology, food supply, topography, seismic activity, substrata, hydrostatic pressure, and temperature.

The biology and the ecology at hadal depths are perhaps no more complicated than at shallower depths. This knowledge gap is a result of insufficient technology and therefore access to this environment. Renewed interest in these deep trenches combined with modern technological advances has created new opportunities to explore and understand the deepest environment on earth.

Among other new international efforts, one such project is currently addressing this knowledge gap and providing a more detailed insight into life in the trenches: the Hadal Environment and Educational Program (HADEEP). HADEEP is funded jointly by the National Environmental Research Council (NERC, U.K.) and the Nippon Foundation (Japan) as a collaborative project between the Oceanlab, the University of Aberdeen (U.K.), and the Ocean Research Institute (ORI), University of Tokyo (Japan).

Conceiving HADEEP

The HADEEP project was conceived during in impromptu trip to a bar in Aberdeen town centre during the Benthic Dynamics conference (March 25–29, 2002). The conference was comprised mostly of participants involved in Sediment Profile Imaging (SPI) cameras. Among those present were Martin Solan, a benthic ecologist, and Alan Jamieson, an engineer from Oceanlab. A few beers later, the conversation turned to "who has taken the deepest SPI image?" The award went to a brave SPI enthusiast from Virginia who had taken an image at 6,000 m despite his camera only being rated to 5,000 m (Diaz, 2004). Several beers later, the conversation meandered into how that could be beaten, which eventually led to where it could not be beaten. That place of course was *Challenger Deep* in the Marianas Trench (~11,000 m). Although the details are now perhaps a bit fuzzy, the night ended with a confident "let's go to the Marianas Trench."

At that time, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) were successfully operating a 12,000-m rated remotely operated vehicle (ROV) called *Kaiko* (Takagawa, 1995; Mikagawa and Fukui, 1999). The next day at the conference, members of JAMSTEC who were also attending were approached by two guys from Aberdeen with an enquiry to deploy a mini-SPI camera on *Kaiko*.

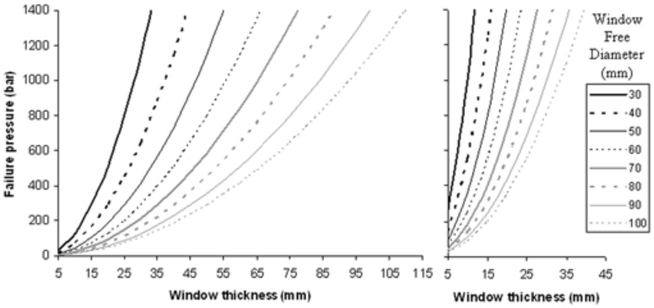
Developing the Hadal-Cam

The following year saw efforts in both Japan and the U.K. to secure funding to develop the technology required for hadal rated instrumentation. The original idea was to design a camera system capable of both SPI imaging and seafloor imaging. This also coincided with a part-time PhD study developing autonomous instrumentation platforms for deep-sea biological studies (Jamieson, 2004). As part of that PhD, pressure vessel and optical viewports were theoretically designed and prototypes were tested to withstand pressures of 1,400 bar (11,000 m operational depth with 3,000 m safety factor). A sum of money was eventually secured from internal Aberdeen University funds to develop a 12,000-m rated video camera that became known as the Hadal-Cam. Although the Hadal-Cam was only one piece of a potentially larger project, it provided an asset in which to secure a larger supporting grant to use the *Kaiko* ROV. The money for developing the Hadal-Cam was awarded on May 19, 2003. Elsewhere on May 19, 2003, the *Kaiko* ROV was tragically lost at sea while surfacing in an emergency during a typhoon (Momma et al., 2004), an unprecedented loss to deep-sea exploration. Meanwhile, it was decided to continue developing the Hadal-Cam. Knowing that any video footage would be of public interest it was important to source a camera "better than TV" quality. A Hitachi HV-D30, 3CCD color video camera was chosen (800 TV lines) with a 2.8- to 8-mm wide-angle varifocal lens. The system was designed to operate autonomously, and video capture was controlled by mission control software, specially developed by John Kinmond at NETmc Marine (U.K.).

The software permits user defined power up/down sequences, repetitions, and start delay. A relay board, with built in microprocessor, was used as the interface between the camera, lights, and recorder and enabled the recorder to power off and on to maximize battery life. The recorder was a modified NETmc Marine DVR Inspector, a high-end broadcast quality MPEG2 recorder with an Opti-base encoder card (type MPG9005). This gave a screen resolution of 704 × 576 pixels. Illumination was provided by twin 50-W lamps, and the entire system was powered by a 12-V lead acid battery (SeaBattery; Deep Sea Power & Light, USA). The camera and lights required in-house customizing to withstand the enormous pressures at hadal depths. The pressure-resistant housings designed by Jamieson (2004) were based on the elementary mechanics of *Roark's Formula for Stress and Strain* (Young, 1989) and prior experience of designing for 6,000 m. To lighten the payload weight of the ROV (or other potential vehicles), titanium 6Al-4V provided the best strength-to-weight ratio and corrosive properties. While the main body of the housing was relatively straightforward, the camera window or "viewport" became the most challenging development. It was apparent that the problem of transparent viewports at high pressure was not a new one, even the crew of the *Trieste I* dive noticed a 2-mm creep of their viewports (Lt. Don Walsh, 2004, personal communication). Based on principles described by Gilchrist and MacDonald (1980), a series of acrylic beveled disc test pieces were pressurized to 1,400 bar. On each cycle, the acrylic crept into the air cavity behind it. The distortion increased with time at pressure, eventually resulting in the entire viewport being squeezed into the housing, that is, baroplastic deformation (see Gonzalez-Leon et al., 2003). No noticeable deformation took place until beyond approximately 800 bar (8,000 m). After a series of pressure tests at the Scottish Offshore Material Centre at the University of Aberdeen, acrylic viewports were abandoned on the grounds of baroplasticity. Further research into materials, viewport shape, and seating design were investigated, and decisions were made with the limited budget in mind. To keep costs low, a plane disc window design was favored as they required less machining, less wasted material, and therefore reduced costs. With acrylic eliminated from the study, borosilicate glass and sapphire discs were tested. Sapphire offered the best solution in terms of size and reliability, whereas borosilicate windows were unpredictable and become disproportionately large. So much so, the equivalent thickness of a plane disc window in sapphire is less than half that of borosilicate (Figure 1) and furthermore did not incur any significant cost increase. The free diameter, that is, the hole that the camera lens protrudes through the housing end cap, was just 30 mm; therefore, a sapphire disc of 60 mm diameter by 15 mm thick, seated on a 5-mm^2 axial quad-ring (40 mm inner diameter) sufficed. This relatively small and cheap solution was then successfully tested to 1,400 bar for up to 24 h.

FIGURE 1

A comparison of window thickness against failure pressure of borosilicate glass (left) and sapphire (right) of varying window free diameters. The equivalent window in sapphire is less than half the thickness of borosilicate.



With the lamp housings, a different solution presented itself. A chance encounter with Gerald Abich at Nautilus Marine Services (Bremen, Germany) led to an idea of using two Vitrovex® glass mini-spheres (100 mm inner diameter). These spheres were design to be small and just coincidentally could hold 1,200-bar pressure. As the optical path of the illumination is not as critical as the camera, the mini-spheres provided another very simple and cost-effective solution. In the end, the 12,000-m rated 50-W lamps cost less than off-the-shelf commercial 50-W lights rated to 6,000 m.

At this point, the Hadal-Cam was not completed as the spiraling costs of titanium had put Ti 6Al-4V beyond the financial limits of the project. So by the end of 2004, all that was achieved was a PhD thesis, two lamps, a sapphire window, the guts of a camera, a bag of deformed acrylic, and a big idea. Following several unsuccessful attempts to secure funding, it seemed that determination and delusions of grandeur alone were not enough.

The HADEEP Project Origins

During 2006, negotiations with our Japanese collaborator, who by then had moved from JAMSTEC to the Ocean Research Institute, University of Tokyo, had opened a dialogue with the Nippon Foundation (Japan). The Nippon Foundation liked the idea and agreed to fund a joint project to investigate life in the hadal trenches. The complication was that although they would support access to research vessels, there was not enough money to actually construct a hadal rated vehicle and there were still no signs of a *Kaiko* ROV replacement. However, things started to fall into place from hereon. Oceanlab, founded by Prof. Monty Priede had been built around a 20-year history in constructing baited landers (autonomous free-fall vehicles) used to image deep-sea fauna. With some consideration of deep-sea ecology and optimal foraging theory, the remoteness from surface derived particulate organic matter should result in animals relying more on carrion falls (dead fish and cetacean carcasses) that should reach the seafloor irrespective of depth. It then seemed logical to extend this deep-sea baited lander expertise to full ocean depths and not go down the mini-SPI route as originally planned. A grant application entitled "HADEEP—Life at extreme depth; benthic fishes and scavenging fauna of the Abyssal to Hadal boundary" was submitted to the NERC (U.K.) and was successful. The application proposed the construction of two hadal rated baited landers and a full-time Postdoctoral Research Fellow. The landers would be a baited video and a baited stills lander. The still imaging technique provides a time course of scavenging fauna to estimate population size whereas the video system would provide behavioral and physiological data of the observed fauna. Around that time, an opportunity of a research cruise was offered by Prof. Hans-Jochen Wagner of the University of Tubingen, Germany, who had secured a 3-week expedition between Samoa and New Zealand on the German research vessel *Sonne*. Although the cruise was primarily mid-water trawling, the cruise path just so happened to transect the Tonga and Kermadec Trenches in the SW Pacific, both of which are deeper than 10,000 m. The cruise left from Samoa on the 1st of July but the funds from NERC were not received until the 1st of February. The shipping time to Samoa was “at least 2 months” leaving just 3 months to design, construct, test, and mobilize the landers from Scotland to New Zealand.

The Hadal Landers

Autonomous landers are comprised of two parts: The delivery system (buoyancy, ballast, structure, and acoustic releases) and the scientific payload (cameras and environmental sensors). The basic delivery system carries and protects the scientific payload within a frame. Buoyancy is coupled to the topside while ballast is coupled to the underside and temporarily held by the acoustic releases. With the ballast on, the lander free falls to the seabed where the autonomous instrumentation perform preprogrammed tasks. By acoustic command from the ship, the releases jettison the ballast weights and the ascension to the surface begins by virtue of the positive buoyancy where it is retrieved by the surface vessel (for further details on lander design see Tengberg et al., 1995; Bagley et al., 2005).

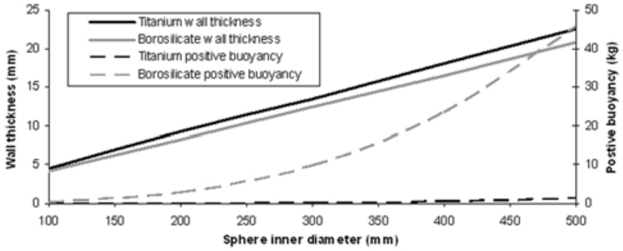
The Delivery System

The structure of the landers were based on existing Oceanlab video tripod landers (for, e.g., Priede et al., 2006) made from marine grade aluminum 5082 but re designed to 3/4 the size. The buoyancy was tethered in off-line modules on a mooring line above the frame. This method permits the landers to be deployed from relatively small ships and can be modified/replaced depending on how the lander evolves. A 45-kg clump of ballast weights were suspended from each of the three legs approximately 250 mm from the seafloor to give a confident drop when triggered. The biggest challenges in the delivery system were sourcing the 12,000-m rated acoustic releases and buoyancy.

For over 10 years, Oceanlab had been using IXSEA acoustic releases, formally MORS and OCEANO. IXSEA were approached about extending their product depth range to 12,000 m. The acoustic releases are a key component in lander operations and thankfully IXSEA did not quite fall off their chair when asked. On the contrary, a couple of months later, four “ultimate depth” 2500-ti acoustic releases arrived in Aberdeen. Two releases were incorporated into each lander, simultaneously coupled to a ballast release catch to provide back-up in the unlikely event one should fail. The releases comprised the standard electronic sub-assembly of the Oceano 2500 Acoustic Release range, rehoused in a titanium grade 5 body tested to 1,420 bar. In good environmental conditions, the acoustic performance allow ranges >12,000 m. The remote communications were provided by the standard TT801 Deck Unit.

FIGURE 2

The required wall thickness (mm) and resulting positive buoyancy (kg) of titanium and borosilicate spheres of varying inner diameter (100–500 mm) at 1,400-bar pressure. Titanium spheres cannot produce significant positive buoyancy at these depths.



There were a few avenues to explore in sourcing the buoyancy: syntactic foam, ceramic spheres, titanium spheres, and glass spheres. The syntactic foam option was unavailable partly due to time constraint and partly due to costs. The ceramic spheres were investigated but that technology at the time was in its infancy and was felt to be too high risk in this application. Interestingly, titanium spheres will not produce significant positive buoyancy at 12,000 m. For example, assuming a design safety factor of 1,400 bar failure pressure, the positive buoyancy generated by any diameter of sphere will be less than 2.5 kg due to the require wall thickness (essentially weight) required to withstand the ambient pressure (Figure 2). Again, as luck would have it, Nautilus Marine Services in Germany, who had previously supplied the mini-spheres, appeared confident they could increase the wall thickness of their standard 17-inch Vitrovex® sphere for 12,000 m operations. The spheres had an outer diameter of 432 mm and an inner diameter of 393 mm (20 mm wall thickness) producing 19 kg of positive buoyancy each. The catch was that they would not be ready in time for the U.K. to Samoa shipment and therefore had to be shipped directly from Germany to Samoa.

One other component to the delivery system is the location aiding devices for when the landers surface. These are typically a strobe light, a VHF beacon, and a flag. The flag was as standard (orange); however, a great deal of time was invested in redesigning the VHF radio and Xenon strobe (Novatech RF-700A and ST-400A, respectively; Cobham Ltd, Canada). These required rehousing into a Nautilus 12,000-m glass sphere as they are supplied as 7,300 m rated. Roger Scrivens at RS Aqua (U.K. agents for both Cobham and Nautilus) randomly suggested sending one of these housings to Nautilus to pressure test it as he had a feeling it was good to 1,000 bar. Some further calculations were done and surprisingly the standard off-the-shelf 7,300 m rated Novatech radios and strobes are capable of 10,000 m operations.

The Scientific Payload

The old plans for the Hadal-Cam housings were reviewed and with the costs of titanium now increasing beyond all reason they were reluctantly redesigned in Stainless Steel UNS32550. The electronics were housed in one large cylinder (later described as a "cannon-barrel") and the camera was housed remotely in a smaller version incorporating the sapphire viewport. The size of the electronics housing was such that it weighed over 100 kg in air and would not fit into any pressure test vessel capable of 1,400 bar. It was therefore tested to 700 bar at Oceanlab with the remaining few thousand meters relying heavily on crossed fingers and Roark's formulas. The Hadal-Cam was positioned on the landers lower deck 1 m off the seafloor. The camera and lamps face vertically down and focused on a 10-mm diameter × 1,000-mm bar where the bait is secured. This produced a field-of-view of 68 × 51 cm (0.35 m^{-2}). The bulkhead connectors and cabling were readily available as standard Impulse 20,000 psi rated wet pluggable series (Teledyne Impulse, USA). When ready to explore the deepest places on earth, it was essential that the depth was recorded. Another chance encounter, this time with Calvin Lwin from SeaBird Electronics Ltd (USA) led to the purchase of two SBE-39 temperature and pressure sensors rated to 10,500 m with an accuracy of 0.0002°C and 0.1%, respectively.

The last item of scientific payload to be sourced was the digital stills camera. With the time constraints, it would be difficult to design and build one in-house. Oceanlab typically use Kongsberg Maritime 6,000 m rated digital stills cameras and so they were approached. Like Nautilus, Kongsberg gratefully agreed to supply such a camera but again could not make the shipment to Samoa with the rest of the equipment; therefore, a third shipment was scheduled to rendezvous in Samoa. The camera was an OE14-208 5-megapixel digital stills camera based on Canon G5 technology. It had a remote flash gun and both were housed in grade 5 titanium. The camera and the flash were powered by a 24-V lead acid battery (SeaBattery; DeepSea Power and Light, USA).

In addition to the landers "high-tech scientific payload," three baited funnel traps, made from garden wire and drainage pipe, were lashed to the feet to collected any small scavenging crustaceans for taxonomic and genetic studies.

The landers were finally assembled, albeit still missing several crucial components, a few days before the shipment date, just in time for a quick dunk in a test tank before loading the 20-foot container destined for Apia, Samoa (Figure 3).

FIGURE 3

An almost complete Hadal-Lander A ready for testing (left). The Hadal-Cam camera housing and sapphire window assembly (top right) and a 50-W lamp housed in a 114-mm diameter mini glass sphere.

Into the Hadal Zone

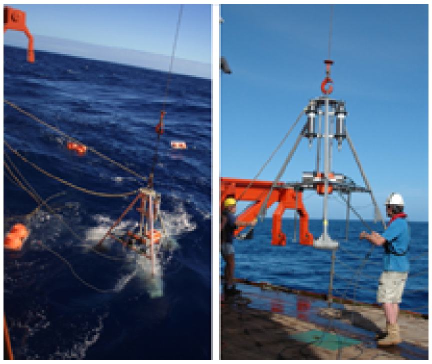
The South Pacific

At the end of June, Drs. Jamieson and Solan and the newly appointed Dr. Toyonobu Fujii met the RV *Sonne* in Apia. After a trying time getting the equipment cleared of customs, it became apparent that there may be problems with the other shipments. The camera eventually arrived with 2 days to spare. On the day of departure, the ship was due to sail at 0930 h. The thirty 17-inch glass spheres finally cleared customs at around 0900 h and were hastily thrown on board in disbelief before transiting to the Kermadec Trench. When exactly they arrived in Apia is still unknown.

The very first time the landers were completely assembled and tested minutes before the descent to 6,000 m on the edge of the Kermadec Trench. The landers were christened, rather unimaginatively, Hadal-Lander A (video; i.e. Hadal-Cam) and Hadal-Lander B (stills). The Hadal-Cam was set to record 1 min of footage every 5 min (1 min on, 4 min off), 120 times, and the stills camera was set to 60-s intervals. Thankfully, both landers returned on command the following morning. Over the next 2 days, the landers were deployed to 7,000 and 8,000 m. Unfortunately, as a result of a fault in the voltage regulation, the Hadal-Lander B stills camera failed to operate. However, Hadal-Lander A was an unprecedented success. The 6,000- and the 7000-m deployments captured both the deepest ever decapods (a family including prawns, crabs, and lobsters), on this occasion the natantian prawn *Benthesicymus crenatus* (Jamieson et al., 2009a), and filmed the endemic snail fish *Notoliparis kermadecensis* alive for the first time (Jamieson et al., 2009b). This snailfish has only ever been trawled once in the early 1950s and the Hadal-Cam managed to capture extensive footage of three individuals swimming and feeding in their natural habitat. The landers were later deployed to 9,000 and 10,000 m in the Tonga Trench. Interestingly, the Tonga Trench is apparently the resting place of the radioisotope thermoelectric generator from the aborted Apollo 13 mission (which supposedly contained ~4 kg of plutonium). The 10,000-m deployment (Figure 4) was a great milestone in the project, proving after all these years the capability for full ocean depth observations. The video footage from 8,000, 9,000, and 10,000 m showed ever increasing numbers of small amphipods (Crustaceans), almost exclusively the endemic species *Hirondellea dubia*. The baited funnel traps managed to capture thousands of amphipod specimens for taxonomy and population genetic studies.

FIGURE 4

The deployment and recovery of Hadal-Lander A to 10,000 m in the Tonga Trench from RV *Sonne* in July 2007.



From an ecological perspective, the cruise was an enormous success and not only gave an insight into what could be achieved and proved that each of the components were capable of 10,000-m operations, which came a great relief to the HADEEP team and the component suppliers alike.

The North Pacific

The RV *Sonne* returned to Auckland, New Zealand, where the landers were shipped to Japan for the next wave of expeditions. Between October 2007 and March 2009, four trench expeditions were undertaken in the NW Pacific: two to the Japan trench (7,100 and 7,700 m) on the RV *Hakuho-Maru*, one to the Izu-Bonin Trench (8,100 and 9,300 m) on the RV *Tansei-Maru*, and one on the RV *Kairei* to the edge of the Marianas Trench (5,500 m), which was later declared a national monument by former U.S. president George W. Bush in 2009. Over the course of the cruises, the landers were upgraded and improved on several levels. Firstly, a 2-L Niskin water bottle (Ocean Test Equipment Inc., USA) was added to each system and were coupled to the ballast release mechanism to collect bottom water for laboratory based oxygen measurements. Also, the environmental suite was upgraded with SBE19plus V2 CTD profilers rated to 10,500 m (SeaBird Electronics, USA). The CTDs provide a temperature, salinity, and pressure resolution of 0.0001°C, 0.4 ppm, and 0.002%, respectively, from the sea surface to the trench floors and were set to sample every 10 s throughout the deployment. The invertebrate traps also received an upgrade. Dr. Fujii, determined to trap "something bigger," constructed a "giant funnel trap" from garden wire and an old sewage pipe, a classic mix of high tech meets low tech, but with amazing results.

The highlights of these cruises were the deepest ever decapods (again; Jamieson et al., 2009a), the deepest ever grenadier or "rat-tail" fish (*Coryphaenoides yaquinae*, family Macrouridae), and the first ever live footage of another snailfish, this time *Pseudoliparis amblystomopsis* (family Liparidae; Jamieson et al., 2009b). Perhaps the most significant single deployment of the project was with Hadal-Lander A at 7,703 m in the Japan Trench in October 2008 when a total of 20 snailfish were seen in view of the camera. This was the deepest footage of fish ever taken and of so many it was truly remarkable. Furthermore, Dr. Fujii's giant trap captured not only three juvenile snailfish, but two five giant amphipods of two species and two gastropods (Figure 5).

FIGURE 5

High tech meets low tech: Hadal-Lander A with the new CTD system pictured on the RV *Tansei-Maru* (left). The large and small funnel traps (top right) which caught the large amphipods (middle right) and the remains of the mackerel bait after 12 h on the trench floor (bottom right).

Due to adverse weather, ship time restriction, and another unrelated electrical fault, Hadal-Lander B was only successfully operated in the 5,500-m Marianas Trench deployments.

At some point in the North Pacific expeditions, the landers developed nicknames: Hadal-Lander A became known as *Alfie* after a long story involving a horse and Hadal-Lander B became known as *Jonah* after its rather incredible run of bad luck.

Technical Evaluation

After 15 deployments in five trenches over 2 years, it is now possible to technically evaluate the performance of the landers (Table 1).

The landers descended to the seafloor at a mean velocity of 45.6 m·min^{-1}, which equates to 3 h 27 min to reach 10,000 m. The average ascent speed was 33.6 m·min^{-1}, resulting in a 10,000-m ascent time of 4 h 40 min. As the landers travelled through various water masses and changes in density and pressure, the descent slowed with depth and after ballast release slowed again during ascent, both by about 6 m·min^{-1} (Figure 6). For practical reasons, a mean terminal velocity, as described by Tengberg et al. (1995), is sufficiently accurate to plan experimental times.

One concern prior to hadal operations was glass sphere fatigue under such immense pressure cycling. To date, only one glass sphere out of 22 regularly used spheres has been retired due to excessive accumulation of glass dust on the inside but no failures at depth have occurred.

The video camera was always set to record 1 min of footage every 5 min (1 min on, 4 min off) 120 times. The 1-min files in MPEG2 were 50.5 megabytes each, resulting in ~6 gigabytes per deployment. The average digital still image size was 1.6 megabyte resulting in ~1.3 gigabyte of images per 12 h on the seafloor.

TABLE 1

Specification summary of Hadal-Lander A and Hadal-Lander B.

Lander	**Hadal-lander A**	**Hadal-Lander B**
Type	Baited Video, CTD	Baited Stills, CTD
Nickname	*Alfie*	*Jonah*
Depth rating	12,000 m	12,000 m
Delivery system		
Acoustic releases	Oceano 2500-Ti UD (x2)	Oceano 2500-Ti UD (x2)
Buoyancy	17″ glass spheres (x13)	17″ glass spheres (x9)
Total positive buoyancy	247 kg	171 kg
Ballast weight (wet)	135 kg (45 × 3 kg)	135 kg (45 × 3 kg)
Vehicle weight	180 kg	110 kg
Total weight (descent)	68 kg −*ve*	74 kg −*ve*
Total weight (ascent)	67 kg +*ve*	61 kg +*ve*
Descent velocity	45.6 m·min^{-1}	33.6 m·min^{-1}
Ascent velocity	54.2 m·min^{-1}	34.0 m·min^{-1}
Scientific payload		
Camera	Hadal-Cam	Kongsberg OE14-208
Camera resolution/format	704 × 576 pixels (MPEG2)	5 megapixel (JPEG)
Camera sample interval	1 min every 5 min	1 min
Camera sample number	120	2000
Battery	12v lead acid	24v lead acid
Camera field of view	68 × 51 cm (0.35 m^{-2})	63 × 47 cm (0.29 m^{-2})
CTD	SBE19plus V2	SBE19plus V2
CTD resolution (S,T,P)	0.4 ppm, 1 × 10^{-4}°C, 0.002%	0.4 ppm, 1 × 10^{-4}°C, 0.002%
CTD sample interval	10 s	10 s
Water sampler	2-L Niskin	2-L Niskin
Funnel traps	30 cm Ø × 40 cm (×1)	None
	10 cm Ø × 30 cm (×2)	
Bait	~1 kg mackerel/tuna	~1 kg mackerel/tuna

The acoustic communications with the landers have been good. Two-way communication between the releases and the deck unit via an 8- to a 16-kHz hull mounted transducer on the *Sonne* provided extremely accurate slant ranges (within 100–200 m of the bottom depth). However, when using the over-the-side remote transducer head, the return signal to acknowledge command execution is not detected until the landers are ~6,000–7,000 m deep depending on location. The release function always executed

FIGURE 6

Free-fall hydrodynamics: The decent and ascent speeds of Hadal-Lander A over 10,000 m in the South Pacific. The lander slows down by ~6 m·min^{-1} during both descent and ascent.

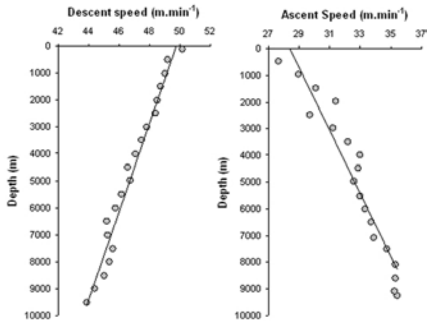
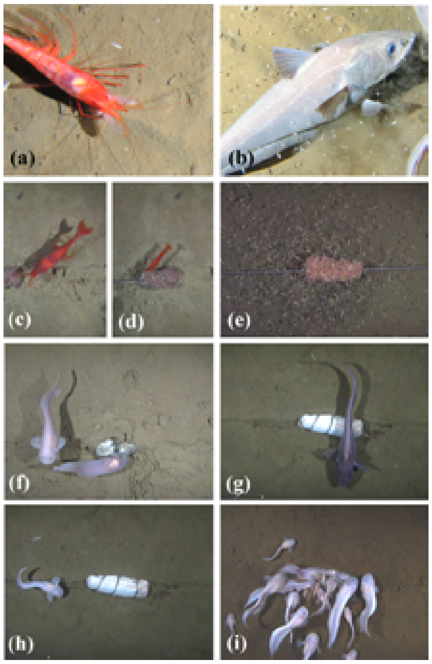


FIGURE 7

Images from the hadal landers: (a–b) Still images of a decapod and a rat tail from Hadal-Lander B from 5,500 m in the Marianas Trench. (c–d) The decapods *Benthesicymus crenatus* and *Acanthephyra* sp. from ~7,000 m in the Kermadec Trench. (e) Swarms of the amphipod *Hirondellea dubia* from 10,000 m in the Tonga Trench. (f) The first and only live footage of the snailfish *Notoliparis kermadecensis* from 7,000 m in the Kermadec Trench. (g) The deepest rat tail (*Coryphaenoides yaquinae*; Macrouridae) ever found, 7,100, Japan Trench. (h) The first live footage of the snailfish *Pseudoliparis amblystomopsis* (Liparidae), 7,100 m, Japan Trench. (i) The deepest fish ever filmed alive, 7,703 m, Japan Trench (*P. amblystomopsis*).



first time but the long delay in acknowledging this can be uncomforting.

Free-fall vehicles are prone to sticking on the seafloor if deployed on soft sediment. Sinking was observed in the Kermadec Trench at around 7,000 m and in particular the deepest Izu-Bonin Trench deployments (9,300 m). There, the lander sunk approximately 15 cm into the sediment (as indicated by the bait arm in the field of view). However, due to sufficient positive buoyancy (post-ballast release) and perhaps aided by the perforated footpads, the landers are sufficiently capable of rising out of soft sediments.

Conclusion

Over these past 2 years, the hadal landers have provided a great insight into the biological community of the hadal zone (Figure 7). Every expedition has revealed something new and unforeseen, such as extending the known depth range of decapods, a large and important crustacean taxa, by over 2,000 m. Likewise, the abyssal grenadiers or "rat tails" are an extremely common family of deep-sea fish, which are now known to extend at least 1,000 m deeper than previously thought. The video footage of the two snailfish has perhaps been the biggest surprise. This new physiological and behavioral information suggests that despite being endemic to >6,000 m they are in fact not unlike their shallow water counterparts (Jamieson et al., 2009b). Furthermore, the Hadal-Cam observations of such a large aggregation at 7,700 m have highlighted the need for reappraising hadal fish communities. The historical trawl records indicate that fish living in the trenches are merely eking out an existence in extremely low numbers. This misinterpretation is apparently caused by the difficulty in trawling at such great distances from the surface, the efficiency of which is even hard to evaluate. The passive nature of a baited camera sitting idly on the seafloor appears far better suited in this application than, for example, trawling, or ROVs.

The uses of deep submergence vehicles such as ROVs are paramount in hadal exploration and the mapping of habitat and infaunal/epifaunal communities but have in the past been unsuccessful in quantifying larger mobile animals. The sighting of a fish at Challenger Deep during the *Trieste I* dive was quickly claimed to be erroneous (Wolff, 1961), and the archives of the *Kaiko* ROV do not contain any noteworthy records of significantly mobile fauna. One tantalizing discovery made within HADEEP was that the species composition and behavioral observations of fish beyond 7,000 where uncannily similar to those described by J.M. Pérès in the *Archimede* Bathyscaph in 1964 (Pérès, 1965). Very specific details relating to, for example, swimming behaviour, distribution, and colorings were almost identical in both studies. Why this is surprising is because the HADEEP records were from the Japan Trench and the *Archimede* records where from the Puerto-Rico Trench, some 4,000 nautical miles apart in different oceans. Unfortunately, Pérès did not take any photographic records nor has anyone since, suggesting there is a diverse and active community inhabiting the Puerto-Rico Trench waiting to be found.

Combining all these technologies will pave the way to a better understanding of the trench environment;

for example, acoustic and photo mapping with selective sampling for biology and geology and *in situ* experimentation combined with more passive short-term observations and long-term monitoring of, for example hydrology, seasonality, food supply, etc.

Underwater technology aside, laboratory based technology has moved on a great deal since the last major multi-trench sampling campaigns in the 1950s. Phylogenetics and biochemical analyses of specimens, such as those collected by the funnel traps (Figure 8), can now reveal evolutionary pathways and food web structures both of which are particularly interesting given the geographic isolation of the hadal trenches.

FIGURE 8

Specimens from Hadal-Lander A funnel traps: (top row) scavenging amphipods from the Japan and Izu-Bonin Trenches, 7,000–9,300 m. (Middle row) A cumacean and a large amphipod from the Japan Trench 7,000–7,700 m. (Bottom row) Gastropods and the snailfish *Pseudoliparis amblystomopsis* from 7,700 m in the Japan Trench.

The HADEEP project has not only provided the marine science community with new insights into life in the deepest parts of the oceans but has also managed to grab the imagination of the public. The publicity surrounding the filming of fish deeper than ever before became international news in October 2008. It was covered by most major news networks and newspapers around the world resulting in public lectures and exhibitions in national science museums and ended up in the top five most watched videos on YouTube.com for a spell. The footage even found its way into the in-car TV screens of the Tokyo underground on the JR Chuo-Line and the JR Keihintohoku-Line and was broadcast to five million commuters per day for 2 days. A lot of this publicity included details of the both the *Galathea* and the *Vitjaz* expeditions and the famous *Trieste I* dive to Challenger Deep, which raised both the profile of hadal science and renewed the interest of these achievements, hopefully inspiring a new generation.

The next step technologically is to upgrade the landers further with acoustic current meters to monitor tidal flow in the trenches and possibly *in situ* oxygen measurements. Funding is also being sought to upgrade the Hadal-Cam with smaller electronics and a higher resolution video camera. The next wave of expeditions will see the introduction of 12,000-m rated fish traps and sediment grabs currently in the design and construction phase. Scientifically, the project will continue aiming to achieve as many deployments in as many trenches as possible to build an extensive archive on which to draw inter- and intratrench comparisons to provide a better understanding of trench ecology and just what is going on in the deepest places on Earth.

Although the NERC-funded component of HADEEP recently came to an end, the Nippon Foundation support continues until 2011. Although further funding is being sought to expand the scientific, technological, and expedition elements, the project is still very much in full swing. Between October 2009 and June 2010, both the hadal landers will be deployed in the Kermadec and Tonga Trenches with help from the National Institute of Water and Atmospheric Research (NIWA) in New Zealand. The landers *Alfie* and *Jonah* will then be reunited with the RV *Sonne* for an expedition to the Peru-Chile Trench in the fall of 2010 before, all going well, returning to Tokyo for a planned series of expeditions to the Japan and Izu-Bonin Trenches in 2011.

As for autonomously following in the footsteps of the *Trieste I* to Challenger Deep, it was once said that "Alfie won't sleep until Challenger Deep." This sentiment still stands.

Acknowledgments

We thank Dr. A.K. Matsumoto, Dr. K. Kita-Tsukamoto, Prof. H. Tokuyama, and Prof. M. Nishida at the Ocean Research Institute, University of Tokyo, Japan, and crew and company of the Research Vessels *Sonne*, *Hakuho-Maru*, *Tansei-Maru*, and *Kairei*. The HADEEP project was funded by the Natural Environmental Research Council (U.K.) and the Nippon Foundation (Japan), with additional support from the University of Aberdeen (U.K.)

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