OCEAN SCIENCE

A Dive to Challenger Deep

A recent manned dive to the bottom of the Mariana Trench heralds new scientific discoveries.

Richard A. Lutz and Paul G. Falkowski

Humans have always been fascinated by the deep sea. Early sketches of submarines in the 16th century led to the construction of the first underwater vehicle in 1623. By the 18th century, submarines were used for warfare. In 1870, Jules Verne created a fictional world of sea monsters and life aboard the mystical submarine *Nautilus* that could descend 20 km into the sea. The novel captured the imagination of millions of people.

Reality caught up with fiction on 23 January 1960, when U.S. Navy Lieutenant Don Walsh and Swiss engineer and oceanographer Jacques Piccard descended in the bathyscaphe *Trieste* more than 10,800 m to the bottom of the deepest area of the world's ocean, the Challenger Deep in the Mariana Trench—and returned home safely. However, *Trieste* was extremely bulky and not designed for exploration. On 26 March 2012, a technologically advanced research submersible was finally ready to brave a return to the site, and another human made that same round trip, reigniting the excitement of exploring the deep ocean. But what James Cameron accomplished during his 7 hours in the *Deepsea Challenger* submersible (see the first figure) was far more than just one more journey to "the abyss." *Deepsea Challenger* is equipped with a hydraulic arm for taking samples and has elaborate lighting and photographic capabilities, enabling state-of-the-art research in the deepest parts of the ocean.

The imagination of the scientific community was sparked in 1977, when three occupants of the submersible deep submergence vehicle (DSV) *Alvin* discovered a chemosynthesis-based ecosystem teeming with life at deep-sea hydrothermal vents at a depth of 2500 m along the Galapagos Rift (*1*). That voyage to the deep was the first in a series of ongoing discoveries about the potential of animals to sustain life based on symbiotic associations with chemoautotrophic microbes in areas of seafloor spreading. It set the stage for decades of biological and geological research with human-occupied vehicles in arguably the most extreme environments on Earth.

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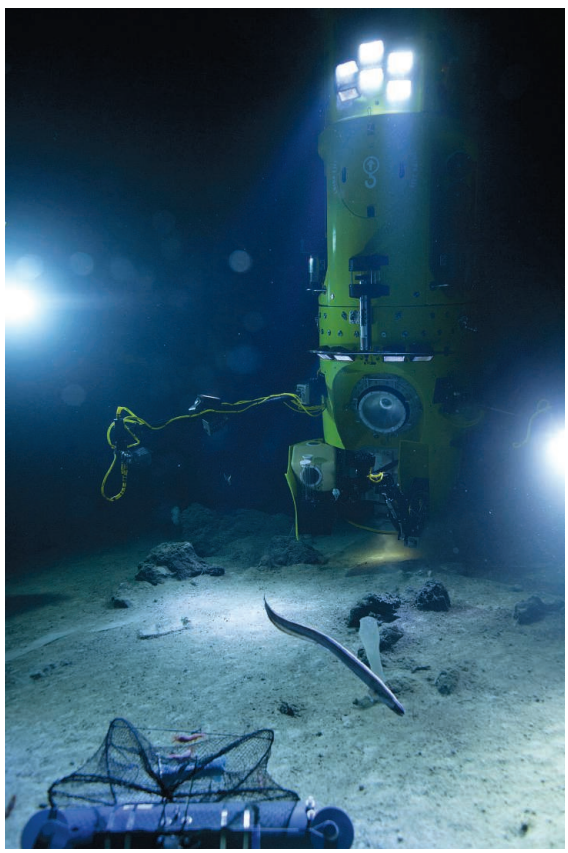

Into the deep. The DSV *Deepsea Challenger*, the one-man deep-diving submarine built by James Cameron, photographed on 1 April 2012 by the unmanned lander, deep ocean vehicle (DOV) *Mike*, built by Scripps Institution of Oceanography/University of California, San Diego. The pair met up at a depth of 1500 m on a checkout dive off Ulithi Atoll after Cameron's dive to the bottom of the Challenger Deep, East Pond, Mariana Trench, on 26 March 2012.

Since the discovery of these deep-sea ecosystems, researchers have spent countless hours in research submarines to experience firsthand these esoteric organisms in their remote environments. The physical reality of seeing the deep sea firsthand is totally different from viewing it on a television screen on the deck of a ship. Scientific exploration of these communities has stimulated interactions among scientists across many disciplines. Their collective and interactive research has provided clues to the origin of life, the reasons behind the phenomenal rates of mineral deposition and organism growth in vent environments (*2*, *3*) and the possibility of life on extraterrestrial bodies (*4*).

Life under pressure. This specimen of *Hirondellea gigas* was collected by ROV *Kaiko* at a depth of 10,920 m in the Challenger Deep.

The deepest-diving human-occupied research submersibles in today's scientific fleets can descend to depths of ~7000 m, thus covering more than 99% of the world's seafloor environments. However, 16 trenches throughout the world's oceans are deeper than 7000 m (*5*). Cameron's extraordinary feat shows that technology has advanced to the point where a vehicle can safely transport its occupant or occupants to the deepest depths of the ocean, providing access to areas that remain essentially unexplored.

In one of the few reported studies of seafloor ecosystems below 7000 m, Fujikura *et al*. used the Japanese unmanned remotely operated vehicle (ROV) *Kaiko* to explore and sample a dense, chemosynthetic-based community dominated by a previously undescribed species of a thyasirid bivalve, *Maorithyas hadalis*, at a depth of 7326 m in the Japan Trench (*6*). Yayanos *et al*. (*7*) isolated an obligate barophilic ("pressure-loving") microorganism from an amphipod collected in the Mariana Trench at a depth of 10,500 m with an insulated trap. The strain grew relatively well at 1000 atm and 2°C (the conditions at the bottom of the Mariana Trench), compared with its optimal growth at 690 atm. It failed to grow below 350 atm.

In 1996, ROV *Kaiko* performed its first sampling dive in the Mariana Trench (see the

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second figure). From sediments collected at a depth of 10,898 m during this dive, Kato *et al*. (*8*) isolated two strains of obligately barophilic bacteria. Growth of these isolates was optimal between 700 and 800 atm, with no growth detected below 500 atm. From sediment samples collected at the same depth in the Mariana Trench, Pathom-aree *et al*. isolated 38 strains of actinomycetes (a group of Gram-positive bacteria) (*9*).

The few bioactive compound screening studies reported to date on deep-sea actinomycetes have yielded extraordinary results. Unique compounds isolated from an actinomycete inhabiting deep-sea sediments in the South China Sea have shown potent activities against three tumor cell lines and also showed antibacterial activities (*10*). Compounds isolated from another deep-sea actinomycete exhibited cytotoxicities against five different human cancer cell lines (*11*).

Given the ongoing scientific interest in chemosynthetic communities, questions concerning the adaptations and tolerance of barophilic organisms to extreme pressures, and the potential medical and economic interest in deep-sea microbes and other organisms (*12*), the largely unexplored ocean environments at depths greater than 7000 m are fertile grounds for scientific exploration. With Cameron's recent journey to the Challenger Deep, the world now has a new technology (see the first figure) capable of transporting humans to these extreme high-pressure environments.

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APPLIED PHYSICS

Solution-Processible Electrodes

Polymer-coated surfaces may provide a low-cost route for processing and fabricating organic-based electronic devices.

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Electronics based on thin-film organic materials offer the promise of low-cost flexible solar cells, displays, and light sources that have the potential to be manufactured on large-area plastic substrates via roll-to-roll printing techniques (*1*). These exciting applications are made possible by the relative ease of processing of organic compounds relative to traditional inorganic semiconductors such as silicon. Unfortunately, fabricating these organic-based devices is still prohibitively expensive because they require several costly vacuum-processing steps to manufacture. One of the key barriers to eliminating these steps, in order to realize a low-cost, all solution-processed device, is finding a suitable low–work function electrode material to replace the reactive metals that are typically used, such as calcium, magnesium, or aluminum. On page 327 of this issue, Zhou *et al*. (*2*) report on a general method of engineering low–work function electrode surfaces by means of polymeric surface modifiers containing simple aliphatic amine functional groups. Their method is applicable to a wide range of different electrode materials and can also be used in most state-of-the-art high-efficiency organic electronic devices, including organic solar cells, organic thin-film transistors, and organic light-emitting diodes.

Although the measurement of the work function of a material was first reported more than a century ago (*3*, *4*) as part of an observation of the photoelectric effect, new methods of engineering stable low–work function surfaces are still at the forefront of scientific discovery. The difficulty in realizing a suitably stable material is that the work function—the minimum energy required to remove an electron from the surface of a solid—scales with the electronegativity of the atoms in the bulk (*5*). As a result, low–work function materials are inherently more reactive and therefore typically require vacuum processing to prevent oxidation of the electrode contacts.

The right solution. The method of polymer-modified surfaces reported by Zhou *et al*. provides the potential to manufacture low-cost solution-processed organic electronics such as an all-polymer solar cell.

Zhou *et al*. circumvented this problem of surface oxidation by starting with more stable high–work function materials, such as gold, and then reducing the electrostatic potential at the surface [work function scales with electrostatic potential (*6*)] by adding a thin coating of polymer surface modifier. Although this approach has been used before, previous surface modifiers have relied on specific chemical interactions between the modification layer and the electrode surface, which only works for particular material combinations. In contrast, Zhou *et al*. used air-stable polyethylenimine (PEI) polymers, traditionally used for enzyme immobilization and carbon sequestration, that strongly physisorb to a wide range of different materials, including metals, oxides, polymers, and graphene. Because PEI is a cationic polymer, it strongly reduces the surface electrostatic potential when applied as a thin surface modification layer, thus lowering the work function.

Zhou *et al*. demonstrated the utility of their method by incorporating low–work function PEI-modified electrodes into various electronic devices, including simple organic diodes, organic solar cells, organic thin-film transistors, oxide thin-film transistors, and organic light-emitting diodes. Remarkably, the performance of the PEI-modified electrodes was comparable to that of standard low–work function metal contacts in most of these devices. Even more impressive, using PEI to lower the work function of the conductive polymer PEDOT:PSS [poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate)], they fabricated an all-polymer solution-processed organic solar cell in which the substrate, anode, active layer, and cathode are

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