Robots in the deep

Out of the blue: the Autonomous Benthic Explorer (main picture and inset) triumphed when it discovered the small hydrothermal vent known as 'Rose Bud' (right) near the Galápagos Islands.

Having overcome problems with reliability, autonomous submersibles are starting to make their mark on marine science. Tom Clarke follows their progress beneath the waves — without getting his feet wet.

The 'Rose Garden' amazed marine scientists when it was discovered in 1979. Hydrothermal vents — outpourings of volcanically superheated water from the sea bed — had been identified just two years before. But this example surpassed all expectations. Covered in bizarre tubeworms, giant clams and ghost-white crabs — an entire ecosystem powered, ultimately, by sulphurous chemicals in the vent's scalding waters — this deep-sea oasis became the poster child of marine exploration, gracing the cover of *National Geographic* magazine.

So imagine the disappointment last June, when scientists returned to the location, some 370 kilometres northeast of the Galápagos Islands, and could find no trace of the Rose Garden. Had it been engulfed in a seafloor eruption, or were the researchers looking in the wrong place? We might still be in the dark, were it not for a robotic submersible called the Autonomous Benthic Explorer (ABE), developed at the Woods Hole Oceanographic Institution (WHOI) in Massachusetts. By hovering some 40 metres above the seabed, ABE mapped the area while recording water currents and temperatures. It confirmed that the Rose Garden was no

more — but showed that a new vent, nicknamed Rose Bud, had sprung up in its place.

ABE's success in solving the Rose Garden mystery, revealed at the American Geophysical Union's meeting in San Francisco in December, is just one sign that such autonomous underwater vehicles (AUVs) are finally beginning to fulfil their scientific promise. Under development for a decade or more, AUVs are designed to tackle tasks that are too dangerous for crewed vessels, or too time-consuming for remotely operated craft that must be steered from the surface. They can also be sent to ocean regions that would otherwise be inaccessible. Understanding what is going on in the ocean "is about being out there at the right time in the right place", says Jim Bellingham, an engineer at the Monterey Bay Aquarium Research Institute (MBARI) in California. In this lottery of time and place, AUVs hold the promise of shifting the odds in oceanographers' favour.

Over the past three years, AUVs have studied algal blooms off the coasts of the United States, tracked stocks of North Sea herring and surveyed major new oilfields. And in the coming months, they will travel beneath Antarctica's ice shelves, investigate toxic red tides in the Gulf of Mexico, and study

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upwellings of nutrient-rich water off the Californian coast. If these pioneering projects prove successful, the oceans of the future could be buzzing with robotic probes — some of them spending months at a time on the move, others lying dormant underwater, waiting to be deployed to study sudden events such as seafloor volcanic eruptions.

Spaced out

Marine scientists like to compare their efforts to study the oceans' vastness to the exploration of space. By this analogy, crewed submersibles are like the Apollo Moon missions: extremely expensive and only able to make fleeting trips. AUVs, on the other hand, could fulfil the role of unmanned space probes, taking payloads of scientific instruments on lengthy voyages to inhospitable locations without risking human life.

At least that has been the theory. In practice, however, AUVs have long had a reputation for being unreliable and unpredictable. ABE's first mission, in 1994, was nearly its last, when the device that jettisons its ballast failed. Unable to ascend from the seabed, it had to be rescued by a crewed submersible. Autosub, an AUV developed at Britain's

Southampton Oceanography Centre, suffered similar ignominy in 2000, when it got stuck beneath an overhanging cliff on the sea floor off the Strait of Sicily. With no reverse gear, it was unable to surface, as it is programmed to do in emergencies.

But advances in distributed network architecture, which coordinates the different computers that govern the aquatic robots' components, together with more sophisticated navigation tools and the growing experience of the crafts' handlers, are now turning AUVs' reputation around. "Not only has the technology matured, it's done so very rapidly," says Gwyn Griffiths, head of the Ocean Technology Division at the Southampton centre.

Paths of discovery

With the worst of their reliability problems hopefully behind them, AUVs have begun to prove themselves. ABE's mission to the Galápagos Rift, home of the Rose Garden, illustrates the potential. Sluggish but highly manoeuvrable, ABE can be programmed to follow a predetermined path, dropped over the side of a research vessel, and left to carry out its task. This allowed the scientists on last June's cruise to leave ABE to investigate the Rose Garden mystery, while they got on with other projects and caught up on some sleep.

Some 2.5 kilometres below the surface, ABE moved back and forth in the gloom in a systematic pattern — "mowing the lawn", as WHOI engineer Dana Yoerger puts it. Using sonar, the craft produced a topographical map of the seabed with 30 times the resolution attainable from a surface ship. "It's like someone switched the lights on," says Yoerger. For those exploring the Galápagos Rift, this illumination is crucial. Anna-Louise Reysenbach, a microbial ecologist at Portland State University in Oregon, who visited the rift in the crewed submersible *Alvin* shortly after ABE's survey, says it was like "hiking with a good map". Previously, she'd have been lost in the wilderness.

The discovery of Rose Bud — the smallest and possibly the youngest hydrothermal vent ever found — is another feather in ABE's cap. The craft's temperature sensor detected a discrete, rising plume of water that was 0.02 °C warmer than the surrounding ocean. This anomaly, too small for *Alvin* to have detected, led researchers to Rose Bud. This tiny vent is just a year or so old, but is already developing its own population of deep-sea creatures, as subsequent visits in *Alvin* have shown.

Whereas ABE is designed to explore the ocean's depths, other AUVs have been built to range far and wide through waters nearer to the surface. The torpedo-shaped Autosub is one such craft. In the past few years, it has found its sea legs, by showing that herring aren't scared away by the engine noise of ships conducting sonar surveys of fish stocks¹, and surveying the whereabouts of schools of krill under Antarctic sea ice².

Next month, Autosub will embark on

perhaps the most challenging AUV mission so far. Led by Adrian Jenkins of the British Antarctic Survey in Cambridge, researchers are sending the 7-metre-long vessel beneath the ice shelf at the base of the Pine Island Glacier in Antarctica, where it floats on the sea (see map, below). Such ice shelves, which form where polar glaciers meet the sea, are central to the recycling of fresh water in the form of snow and ice back into the oceans. About 1,000 cubic kilometres of fresh water are thought to melt into the ocean from the underside of Antarctic ice shelves each year, and measurements of ice volumes made at the surface and of the speed of ice-shelf glacier movement suggest that this process may be speeding up³. Yet no one has studied what's happening beneath the ice directly. "It's a total black box," says Jenkins. "We just don't know what's driving the changes there."

Venturing under the Pine Island shelf, which measures some 70 by 30 km, Autosub will use temperature and salinity sensors to measure the rate of melting along its underside. It will deploy an acoustic doppler profiler to detect ocean currents, and sonar to map the topography of both the sea bed below and the ice above. A sampler on board will also return water from beneath the shelf for lab-based analysis. With a range of 500 km and no need to communicate with the surface, Autosub is one of the few devices that are capable of taking these measurements in such a hazardous environment. "It opens a whole new window onto processes within polar oceans," says Jenkins.

If successful, the Pine Island mission will be followed next year by a more ambitious excursion under the Ronne Ice Shelf — which is the size of France and floats on the Weddell Sea. Autosub is fitted with a state-of-the-art gyroscopic compass, and will also

carry an emergency acoustic beacon to signal for help if it gets into trouble. But if anything goes seriously wrong any distance from the edge of an ice shelf, Autosub's handlers accept that they will never see the craft again. "With everything you put in the sea, you have to be prepared to lose it," says Griffiths. At least, he muses, the £850,000 (US\$1.37-million) submersible "would have gone down in the service of science".

Other researchers are working with smaller, cheaper AUVs, where the stakes are somewhat lower. Since the late 1990s, researchers at the Coastal Ocean Observation Lab at Rutgers University in New Brunswick, New Jersey, have been using 1.5-metre Remote Environmental Monitoring Units (REMUS), originally developed at WHOI, to study coastal processes. These AUVs look like miniature versions of Autosub, and operate for only a few hours, as opposed to days, at a time. Even over such short periods, however, they can be deployed from near the shore to study the movement of sediment, the role of waves in oxygenating water, or the effects on the coastal environment of algal blooms and discharges from rivers. "You can put them in the back of a truck and drive them to where they're needed," says Scott Glenn, an oceanographer at Rutgers.

Glenn's team is now starting to deploy

Chilly challenge: Autosub (right) is set to study freshwater melting under the Antarctic ice at Pine Island and, if successful, the Ronne Ice Shelf.

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REMUS in combination with graceful long-duration devices called Slocum gliders, to study the formation of toxic 'red tides', caused by algal blooms, in the Gulf of Mexico off Florida. The gliders, around 2 metres long, operate on much the same principle as their airborne counterparts. Their 'wings' allow them to cover long distances while gradually sinking through the water, and a rudder enables them to stay on course. On reaching the bottom of a predetermined trajectory, the gliders then use a battery-powered pump to change their buoyancy and float straight to the surface. There they use a global-positioning-system device to establish their location, adjust their rudder accordingly and glide downwards again. Because they don't rely on a power-sapping motor, the gliders can sawtooth their way back and forth across an area of interest for days or even weeks at a time.

Glenn hopes that the combination of gliders and REMUS will help to explain how the mysterious red tides form, perhaps revealing whether they are natural phenomena or a consequence of human activities such as agricultural run-off or watershed management. The gliders will provide baseline information on the presence of algae and currents, and on water temperature and salinity, while REMUS will be deployed to obtain more detailed measurements from the most interesting parts of an algal bloom.

At MBARI, Bellingham has also been working with combinations of gliders and powered AUVs — in his case, mid-sized craft called Dorados. This summer, he will contribute to a US Navy-funded study of upwelling in Monterey Bay. As well as supporting a huge array of marine life, upwelling zones are ideally suited to studying mixing of ocean water of different temperatures and salinities. The project, which involves 20 institutions, will deploy sensors on aircraft, ships, AUVs and buoys. Called the Autonomous Oceanographic Sampling Network, the study is seen as a pilot project for future integrated studies of the physical properties of large expanses of ocean over extended periods.

Looking to the future, Glenn and Bellingham want to give teams of AUVs working in concert even more autonomy. With the help of Naomi Leonard of the Dynamical Control Laboratory at Princeton University in New Jersey, they hope to get gliders to act like swarming insects. Using software algorithms that

Slocum gliders can cover huge distances cheaply.

Super subs: Dorado explorers could find use in a range of scientific and military applications.

allow a glider to choose between several different simple behaviours, they envisage fleets of them behaving as if they possess a collective intelligence — surfacing, radioing their position to a central control centre, and then plotting their next moves after learning of the position and behaviour of their fellows. "We will have smart societies of gliders," says Glenn.

Oiling the wheels

Glenn's confidence stems in part from the growing interest of the military and the oil industry in AUVs — which is likely to spur investment and technological progress. Burgeoning oil prices and depleted shallow-sea reserves are seeing oil companies prospecting in ever-deeper waters, where AUVs have distinct advantages. The US Navy, meanwhile, has funded the development of the technology because it is interested in AUVs as mine hunters, and to survey the sea bed near coastlines before amphibious assaults. It is no coincidence, for instance, that Bellingham's Dorado AUVs fit snugly within a submarine torpedo tube — and he has founded a company called Bluefin to market a version of the craft, with the military as his biggest client.

There's certainly room for technological improvement. Extending battery life is a major issue, but cutting-edge technologies cannot always be adapted for use in AUVs. For example, Autosub currently runs on 5,000 standard 'D' batteries, more commonly used to power flashlights or transistor radios. Although advanced lithium batteries are lighter and far more powerful, they are too costly to deploy in risky missions under Antarctic ice.

As well as developing such basics, AUV enthusiasts are working on specific technological improvements that will increase the submersibles' value to academic scientists. Until now, AUVs have generally had to be extensively rebuilt to equip them with the suites of sensors that are required for specific scientific missions. But Dorado and REMUS vehicles now have a payload bay into which instruments can be placed. This flexibility, Bellingham suggests, will encourage oceanographers to dream up applications that AUV engineers haven't thought of. "Then they will really become owned by the scientist," he says.

Griffiths envisions future AUVs spending their entire lives in the ocean, stopping only to charge their batteries and download data. New

versions of the gliders, meanwhile, can already generate electrical energy as they pass through a thermocline, a sudden change in temperature beneath the surface waters in the open ocean — which could allow them to remain at sea for months on end. And at WHOI and MBARI, engineers have developed underwater docking stations for their AUVs.

In the future, such stations could allow AUVs to operate independently from surface research vessels — perhaps sitting moored at key positions in the ocean to be activated when a scientifically interesting phenomenon kicks off. An AUV such as ABE, for instance, could be docked near to an active undersea volcano in the hope of catching it erupting. Only one such event has ever been observed⁴ — by the time a research vessel gets to the site, the action is usually over.

While prototype docking technology is now available, it will require trial and error to perfect. Early efforts to charge batteries at docking stations, for example, caused hydrogen gas to build up in the AUVs' pressurized hulls. "We were turning them into bombs," says Bellingham.

But if the technology develops as anticipated, AUVs could become a powerful extension of another concept on oceanographers' drawing-boards: permanent moored or ocean-bottom observatories connected to the shore by power and communication cables. Small examples already exist, off the New Jersey coast and in Monterey Bay, and the technology could in future allow oceanographers to communicate directly with AUVs over the Internet. Then it will be possible to explore the deep without ever leaving the lab. ■

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Autonomous Benthic Explorer

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Autosub

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