How does the Southern Ocean help protect our planet?

The Southern Ocean circulation system is vital for redistributing heat, carbon and nutrients around the world. It also plays a significant role in absorbing carbon dioxide from the atmosphere, having sequestered ~40% of anthropogenic CO_2 absorbed by the oceans. **Associate Professor Julie Trotter** and **Professor Malcolm McCulloch** from **The University of Western Australia**, and **Dr Paolo Montagna** from the **Institute of Polar Sciences** in Bologna, Italy, are working to understand the complex interactions between the Southern Ocean and global climate.

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PROFILES

Field of research
Marine Geochemistry

Research focus
Investigating environmental changes and ocean-atmosphere interactions in the Southern Ocean

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TALK LIKE A ...

MARINE GEOCHEMIST

Anthropogenic — describing the influence of human activity on the natural world

Biota — the plants and animals living in a particular place

Calibration equation — used to convert geochemical proxy data to a specific environmental parameter

Cryosphere — the frozen parts of the planet, including ice caps and sea ice

Ecosystem — the living organisms and physical environment of a specific area

Geochemical proxy — a chemical method that measures specific compositions of a natural archive, that reflect particular environmental conditions when the organism grew. For example, the ratio of trace elements, such as lithium/magnesium, in a coral skeleton can tell us about the temperature of the seawater in which the coral grew

Isotope — different atomic forms of the same element that have the same number of protons, but a different number of neutrons, and so have different atomic masses

Ocean acidification — a reduction in the pH of the ocean resulting, largely, from the absorption of increased atmospheric carbon dioxide

Phytoplankton — microscopic marine algae that form the basis of most marine food webs

Sequester — to store away

The Southern Ocean is one of the windiest places on earth. Encircling the continent of Antarctica and uninterrupted by land, the polar winds drive the world's strongest ocean current system, the Antarctic Circumpolar Current (ACC). The ACC directly links the Pacific, Atlantic and Indian oceans, giving it a pivotal role in the circulation of water through the world's oceans.

The ACC draws cold, nutrient-rich waters up from the deep ocean, some of which flows southwards where it eventually sinks, but most overturns to flow northwards and into the world's upper oceans, redistributing heat, carbon and nutrients. These northward flowing waters are responsible for nearly three-quarters of global marine biological production, with one of their first stopovers being the mid-latitude submarine canyons off southwest Australia.

These previously unexplored canyons, within the Bremer Marine Park and

Collecting Desmophyllum cup corals and Acesta bivalves with vacuum suction using ROV SuBastian. Hood Canyon, 866 m.
© Schmidt Ocean Institute

Perth Canyon Marine Park, as well as sites in the Ross Sea, are being studied by Julie Trotter and Malcolm McCulloch from the University of Western Australia and Paolo Montagna from the Institute of Polar Sciences. They use the chemical compositions from live and fossil coral skeletons, collected from shallow water reefs to deepwater habitats, to better understand both human-induced and long-term natural changes occurring in our oceans. One important question that the team is addressing is whether the role that the Southern Ocean plays in absorbing carbon dioxide (CO_2) is changing. This occurs as the upwelling of deep, nutrient-rich waters fuel blooms of phytoplankton, which consume carbon from the water. When the phytoplankton die, they sink into the depths, taking the carbon with them and sequestering it in the deep ocean.

With warming of the Southern Ocean and overturning circulation now occurring closer to the Antarctic margin, climate change may be short-circuiting the ability of the Southern Ocean to absorb large amounts of CO_2 from the atmosphere. The Ross Sea and the SW Australian canyons are ideal places to study how Southern Ocean overturning circulation and CO_2 uptake change through time. The canyons, being more easily accessible than the distant and harsh environments nearer Antarctica, are sourced by waters traversing the critical Southern Ocean zone of high phytoplankton productivity, which now mainly drives high CO_2 uptake. Studying ancient fossil corals from the canyons is also important because during the ice-ages, the opposite may have occurred when the northwards flowing waters were stronger.

What is the team hoping to discover?

Despite its global importance, the Southern Ocean is the least studied ocean in the world, largely due to the logistical and practical challenges of working in such an isolated, hostile environment. One of the team's main focuses is to collect and interpret new environmental data to increase our knowledge of the ecosystems, biodiversity and changes that have occurred at different depths and sites in the Southern Ocean. Julie, Malcolm and Paolo collect live and fossilised corals, and analyse their skeletons to reconstruct what the Southern Ocean was like in the past, and how it has changed between then and today. Understanding these changes can help researchers make predictions about how the Southern Ocean will change in the future, and how that might affect other regions. As the amount of CO_2 in the atmosphere continues to increase at an alarming rate, the Southern Ocean could change dramatically, potentially disrupting the distribution of nutrients, heat and oxygen, and threatening ecosystems all over the globe.

What are geochemical proxies?

Geochemical proxy data are specific chemical compositions measured from natural physical archives that tell us about the environmental conditions when the organisms grew. For example, the relative amounts of certain elements that a coral takes into its skeleton (archive), such as lithium/magnesium, magnesium/calcium, and strontium/calcium (proxies), are largely dependent on the temperature of the surrounding seawater. If researchers measure some of these ratios in coral skeletons, they can learn about the temperature of the surrounding seawater when the coral grew its skeleton. Similarly, barium/calcium ratios can be used as a proxy for river runoff or nutrients in seawater.

How are samples collected?

In shallow tropical waters, large, long-lived coral heads are cored using underwater drilling equipment while SCUBA diving. However, to collect deep-water corals (100s to 1,000s of metres deep), the team needs to use remotely operated vehicles (ROVs), which are like mini remote-controlled submarines, tethered to the ship and controlled by joysticks. When collecting samples from the deep canyon systems off SW Australia, the team launched an ROV from the oceanographic research vessel called *Falkor*. The not-for-profit Schmidt Ocean Institute provides its ship and ROV to oceanographers all over the world through a competitive process. This is especially important for marine scientists conducting research in Australia where, despite having one of the longest coastlines, there are no locally available research ROVs.

As well as corals, the team collects samples of seawater that the corals grow in. They deploy a large instrument called a CTD-Rosette system, which collects water when triggered at specific depths while also measuring properties, such as temperature, salinity and oxygen. Much of their analyses of seawater samples and coral skeletons happens back in the lab where they use expensive, sophisticated equipment, such as mass spectrometers (which measure the concentration of elements or their isotopic ratios). Julie, Malcolm and Paolo can compare the CTD readings and chemical analyses of seawater to the measurements of specific proxies in the skeletons from live corals. These allow them to derive calibration equations that are applied to older specimens to reconstruct past changes in seawater conditions.

What have proxy data revealed?

In addition to using temperature proxies to track climate change in modern and fossil corals, the team has studied another type of proxy that is only dependent on the isotopic composition of the element measured, for example, the stable isotopes of boron that depend on the seawater pH. Another is the radioactive isotope of carbon (radiocarbon), best known for dating carbon formed at the Earth's surface from processes involving atmospheric CO_2.

Their studies of boron isotopes in corals from shallow water reefs, temperate environments, and deep waters led Julie, Malcolm and Paolo to discover that certain types of corals can increase the pH of their calcifying fluid, which they use to build their carbonate skeletons. This is important because the pH of the seawater is decreasing as the oceans absorb more of the CO_2 that human activity produces, which is making it more acidic (ocean acidification). This makes it harder for corals to build their skeletons, and even more so for some deep-water corals that already live in low pH environments. However, the team's discovery provides some hope that some coral species may be able to adapt to the increasingly acidic conditions.

By combining measurements of radiocarbon and uranium-thorium ages from ancient coral skeletons, the team has been able to track changes in the uptake and storage of atmospheric carbon in the deep waters in the SW Australian canyons. The deep-water corals living in the canyons during the last glacial period, about 20,000 to 25,000-years ago, recorded major changes in the Southern Ocean's circulation, which resulted in the storage of higher amounts of CO_2 in the deep ocean. The team is also reconstructing ocean temperatures and nutrients from this period of major changes in climate and ocean dynamics.

Ocean circulation is vital for the sequestration of CO_2. Changes in ocean dynamics have direct implications for carbon uptake and storage, which in turn influences the chemistry and productivity of ocean waters and, consequently, the entire climate system.

How does the melting of Antarctic ice affect circulation in the Southern Ocean?

As Antarctic ice melts, it increases the amount of freshwater flowing into the Southern Ocean. This decreases the salinity of the seawater, making it less dense and preventing it from sinking down to the deep ocean. This has the potential to disrupt the Southern Ocean's circulation system, as well as its ability to sequester carbon to the deep. As a result, in addition to increasing sea levels, the melting of Antarctic ice could have global implications for distributing heat, oxygen and nutrients throughout the world's oceans.

What's next for the team's research?

Julie, Malcolm and Paolo are hoping to learn more about the effects of meltwater in the Southern Ocean. To do this, they will have to use ice breakers (specialised ships) and ROVs to collect deep-water coral samples from the very cold waters near the Antarctic continent. These samples could reveal how melting ice affected Antarctic waters in the past, and the team is also hoping to learn more about how different water masses contribute to the ice melt.

The team is continually collecting new samples and searching for new geochemical proxies to help understand these complex processes. In the face of global climate change, it is more important than ever that we understand how ocean systems work and interact with the atmosphere and cryosphere. With carbon emissions continuing to rise, changes to the Southern Ocean are inevitable, which will impact the world's oceans, their ecosystems and global climate.

About *marine geochemistry*

Marine geochemistry is the study of the chemical composition of seawater, the sediments that sit at the bottom of the ocean and the marine biota. Many different factors can affect the chemistry of seawater including temperature, ocean circulation, biological and hydrothermal activity and ice melt.

Human activities can also affect the chemical make-up of seawater. For example, fertiliser run-off from farming can wreak havoc on coastal ecosystems. The excessive amounts of CO_2 being released into the atmosphere from human activities have begun to significantly alter the chemistry of the world's oceans as they continue to rapidly absorb atmospheric carbon. Scientists from many different disciplines are devoting their careers to investigating these impacts.

How important is collaboration in marine geochemistry?

Cross-disciplinary collaboration is essential due to the complexities of our oceans and their interactions with the atmosphere, cryosphere and biosphere. An holistic and integrated approach is needed to obtain a clearer understanding of these complex data, so collaboration between geologists, geochemists, oceanographers, biologists and modellers is important.

For Julie, Malcolm and Paolo, collaboration has been vital. Most of the geochemical analyses have been done in the state-of-the-art labs at The University of Western Australia, whilst the Institute of Polar Sciences has provided many important coral specimens and complementary expertise needed to study them. Following a competitive assessment of their research proposal, the Schmidt Ocean Institute partnered with the team, generously providing its research vessel, remotely operated vehicle (ROV), and the crews needed to pilot them.

Co-ordinating work with colleagues can prove to be challenging, especially when they are living halfway across the world in a different time zone. Although technology allows meetings to take place online, working side-by-side is usually more productive and enjoyable.

Despite the challenges of cross-disciplinary research, the rewards make it worthwhile. Researchers are exposed to new approaches and perspectives which allows problems to be tackled with innovation and creativity. Beyond this, travelling overseas can be an inspiring experience, and researchers often make life-long friends when they are involved in this kind of work.

Where do marine geochemists work?

Marine geochemists spend much of their time in laboratories or on research ships. One of the first jobs on board is to collect bathymetry data using multibeam echosounder systems, which shows researchers how the depth of the ocean changes below the ship and provides 3D reconstructions of the seafloor. This helps them find suitable locations to collect their samples.

Work on a research ship also involves collecting samples of seawater, sediments and, in the case of this research, coral specimens. Some initial analyses can be conducted on the ship. However, more in-depth geochemical analyses are conducted back on shore in labs, for example, using high-tech mass spectrometers to analyse the chemical compositions of coral skeletons and seawater samples.

What research opportunities will be open to the next generation of marine geochemists?

Technological advancements will open a lot of doors for future marine geochemists. Some of these advancements may make it easier to conduct in-depth chemical analyses whilst still on the research vessel. These advancements, as well as improvements to ROVs and fully autonomous underwater vehicles will allow researchers to get more information about their samples whilst at sea. This will allow them to make real-time decisions and work more efficiently, and will also open up new research directions.

Collecting black coral, Leiopathes, using ROV SuBastian. Hood Canyon, 717 m. © Schmidt Ocean Institute

Explore careers in *marine geochemistry*

- Marine geochemists of the future will need an extensive skill set. You will need cross-disciplinary knowledge with a background in chemistry, statistics, geology and oceanography, good communication skills, networking abilities and good technical skills to operate lab equipment.
- As a marine geochemist, you will be working with a wide range of scientists from many different disciplines. You should have a basic understanding of these disciplines so that you can communicate with other researchers and share ideas.
- There are many societies related to marine science, which you can explore to keep up to date with the latest research. Some of these societies include The Challenger Society for Marine Science (**challenger-society.org.uk**), The Australian Marine Science Association (**amsa.asn.au**), the European Marine Board (**www.marineboard.eu**), the EuroMarine Network (**euromarinenetwork.eu**), International Council for the Exploration of the Sea (**ices.dk**) and the Intergovernmental Oceanographic Commission (**ioc.unesco.org**).

Pathway from school to *marine geochemistry*

- Studying STEM subjects at school is important. Chemistry, biology, physics, geology and statistics could all prove very useful.
- Attend summer schools when possible and contact your local university or college to see if they have any internship opportunities.
- Studying oceanography, geology, chemistry or environmental sciences as a bachelor's degree is a good place to start.
- Spending part of your educational career abroad at reputable institutions with specialist labs can be very beneficial.
- Volunteering on oceanographic research cruises is a great way of getting practical experience and can be very exciting!

"MY CAREER HAS ALSO BEEN SHAPED BY WORKING FOR EXTENDED PERIODS IN WORLD-CLASS RESEARCH INSTITUTES"
PAOLO

Meet *Paolo*

I think I became a traveller first and then a scientist. When I was a kid, I used to travel to remote places with my parents. I visited Tanzania when I was six, then the US national parks, the Baltoro Glacier in Pakistan, Papua New Guinea and Borneo. One of my professors at college was a geologist and he introduced me to the main geological theories and periods. After college, I studied geology at university and, during summer holidays, I worked as a geological guide for small to medium-sized travel groups in isolated geographical areas, such as the Himalayan region (Kashmir and Ladakh), South America (Chile and Bolivia) and Iceland. This gave me the opportunity to discover unique places, where geology is the undisputed protagonist, with high mountains, massive glaciers, volcanos and salt lakes. Since I was a kid, I have been fascinated by nature, fossil remains and rocks, and I have always enjoyed the sense of freedom and curiosity of the world. I think all this shaped my character and my passion for science and research.

My career has also been shaped by working for extended periods in world-class research institutes in Australia, USA, Spain and France. Having the opportunity to meet world renowned geochemists and paleoceanographers helped build my scientific knowledge and improve my analytical skills.

As a PhD student, post-doctoral fellow and visiting research scientist (~6.5 years abroad for research training), I have worked in six of the best equipped laboratories in the world (Australian Institute of Marine Science, Australian National University, University of Barcelona, Lamont-Doherty Earth Observatory, Laboratoire des Sciences du Climat et de l'Environnement, Paris-Sud University and The University of Western Australia), with state-of-the-art laboratory facilities, including experimental tanks for coral cultures, ultra clean labs and mass spectrometers used to analyse trace elements, stable and radiogenic isotopes.

I have participated in 20 oceanographic missions to the Mediterranean Sea, Atlantic, Indian and Pacific Oceans, as well as the Ross Sea off Antarctica, and I have also been involved in several SCUBA diving expeditions worldwide.

I always try to have a few options (plan A, B and C) in case something goes wrong, and I try to organise things (lab and field work) by checking all the details.

My proudest achievement has been the discovery that phosphorus concentration within the skeleton of corals is directly proportional to the ambient seawater phosphorus and can be used as a paleo-nutrient proxy. This finding was published in *Science*. In the future, I want to continue to follow my passion for research, making the most of new challenges and opportunities and helping students and young researchers to path their careers.

Life as a paleoceanographer in three words:
Curiosity-driven, experimental, adventurous.

Meet *Julie*

I've always been interested in the natural world, it's diversity, breadth and complexity. My high school science teacher's passion for geology and palaeontology was particularly inspiring. At university, my focus was mostly on geology and palaeontology, so I spent my early career as a palaeontologist. Later, when I had the opportunity to work on joint geochemistry and palaeontology projects, I discovered the importance of geochemistry and how it can be used to advance almost any science discipline.

I have been lucky to have worked in many different field settings: such as the Australian outback, SCUBA diving in the Great Barrier Reef, geological field work in Morocco, Siberia and Argentina, and exploring the ocean depths in the southwest canyons offshore Western Australia. These experiences fuelled my interests in Earth sciences and have drawn me to work with skilled and enthusiastic colleagues from different countries.

I was exposed to the world of geochemistry while working at The Commonwealth Scientific and Industrial Research Organisation (CSIRO) with some wonderful mentors. Those mentors encouraged me to pursue a geochemistry-based PhD at the Australian National University (ANU), that would also use my palaeontological expertise. This unusual combination of skills allowed me to bridge knowledge and communication gaps between these disciplines, and to develop new approaches to better understand environmental changes that occurred over geological and modern timescales.

> **“I DISCOVERED THE IMPORTANCE OF GEOCHEMISTRY AND HOW IT CAN BE USED TO ADVANCE ALMOST ANY SCIENCE DISCIPLINE.”**

I have been very fortunate to have worked in state-of-the-art facilities at ANU and UWA, with world-leading researchers at the cutting edge of science. At ANU, I developed expertise in high resolution in-situ mass spectrometry analyses (laser; ion microprobe) to extract environmental records from tiny marine microfossils (conodonts). At UWA, I helped establish a state-of-the-art Clean Laboratory and Mass Spectrometry geochemistry facility, and expanded my research into recent and modern coral geochemistry, especially deepwater corals.

Perseverance, breaking down the issues, thinking laterally and talking to colleagues, including those with different skills, experience and perspectives, helps with overcoming obstacles. Working through problems with colleagues is extremely rewarding. Looking for different ways to solve a problem and thinking 'outside the box' invariably delivers. If not, take a break, refresh and return with a clear mind. Keeping thorough and accurate records allows you to backtrack easily when troubleshooting unexpected results.

My proudest achievements in science are having contributed new approaches to extract and interpret environmental records from different biogenic archives. Oxygen isotope records determined from single conodont specimens for the first time, using an ion microprobe, showed that major global cooling spurred one of the greatest biodiversification events in Earth's history. Its now widespread application is greatly expanding our knowledge of Palaeozoic and Mesozoic climates and ecosystem.* In the modern realm, revealing that some corals upregulate the pH of their calcifying fluid has significantly enhanced our understanding of their susceptibility to ocean acidification. Most recently, leading an international team to research SW Australia's previously unexplored submarine canyons has been a great privilege, not only as the first to see these incredible deep-sea environments but, most importantly, to reveal them to the world.

Life as a geochemist in three words: Complex, cross-disciplinary, rewarding

** Visit the British Geological Survey's website for a geological timechart:* ***www.bgs.ac.uk/discovering-geology/fossils-and-geological-time/geological-timechart***

ROV SuBastian being launched from the RV Falkor to explore the SW Australian canyons © Schmidt Ocean Institute

The team's *top tips*

- Develop and apply your own critical thinking and skill sets to address what you think are important meaningful questions.
- Do not stop studying.
- Visit, live and work in other countries, explore other research environments and directions, take all the opportunities that present themselves.
- Establish a positive, engaging and supportive network of colleagues.
- Hard-work, perseverance and a critical mind are key attributes.
- Don't follow 'the pack' – explore new things or different approaches.
- Have an open mind and get involved in different research areas to expand your skill-base and knowledge. Having diverse skillsets and undertaking cross-disciplinary research is invaluable.
- Take (or make) any opportunity to work in state-of-the-art laboratories with engaging scientists to learn as much as you can.
- Most importantly, select interesting research projects that inspire you.

Meet *Malcolm*

I grew up in a modest sized coastal city called Busselton, located in Geographe Bay in Western Australia. The name 'Geographe' comes from a ship that was part of one of most important scientific expeditions of its time. In addition to its interesting 'scientific' origins, Busselton has relatively calm waters and the longest jetty in the southern hemisphere. These all contributed to my 'natural interest' in the marine realm.

Because of my interest in the physical world, I decided to study STEM subjects. After completing my undergraduate studies, I undertook a Master of Science thesis under the guidance of Professor John deLaeter. John, and later my PhD supervisor, Jerry Wasserburg at the California Institute of Technology, were my most influential mentors.

I've been fortunate to have had a number of 'eureka' moments. Several occurred at The California Institute of Technology where, under Jerry's tutelage, we discovered the first clear evidence for distinctive heavy-element isotopic signatures of ancient nucleosynthetic processes that ultimately led to the formation of the early Solar System.

I was also keen to work in the marine realm, so at the Australian National University I commenced working on dating fossil coral reefs and sea levels changes, and then proxies for ocean temperature changes. These interests then focused on the present-day Great Barrier Reef (GBR) examining both its temperature and bleaching history, as well as providing the first geochemical record of much increased terrestrial runoff into the reef, which could be clearly attributed to 'European' style land-uses (especially cattle grazing). I'm very proud of this work as it provided some of the most definitive scientific rationale for improved land use practices in the GBR and elsewhere.

Here at UWA, the most exciting development, and my proudest achievement to date, was the discovery of how corals up-regulate the pH of their calcifying fluid and the role of symbionts (organisms living in symbiosis with another) in suppling additional dissolved inorganic carbon to the fluid. This now provides a more fundamental level of understanding of the limitations of coral resilience to climate change and especially their 'Achille's heel', coral bleaching, due to greenhouse warming of the oceans.

I overcome obstacles with persistence and some measure of patience, but with the realisation that you also need to take responsibility for developing the essential capabilities needed to undertake novel research. Also, working as a team with people who have complementary skills and genuine interests always helps.

I've been fortunate to have had the opportunity to make significant science contributions, initially in cosmochemistry, then isotopic tracing of geologic processes in the solid Earth sciences, and most recently in environmental geochemistry, the latter with respect to coral reefs. Not only has it given me the chance to work in what is unquestionably one of the most awe-inspiring environments, but also to make meaningful contributions to understanding the ever-increasing risks and challenges that this unique environment now faces.

My aim for the future is to better understand and promote a sustainable future for our marine environment.

Life as a geochemist in three words:
Challenging, rewarding, enlightening.