Eos

How Offshore Groundwater Shapes the Seafloor

The MARCAN project, launched last January, is working to fill a gap in our knowledge of how freshwater flowing underground shapes and alters the continental margins.

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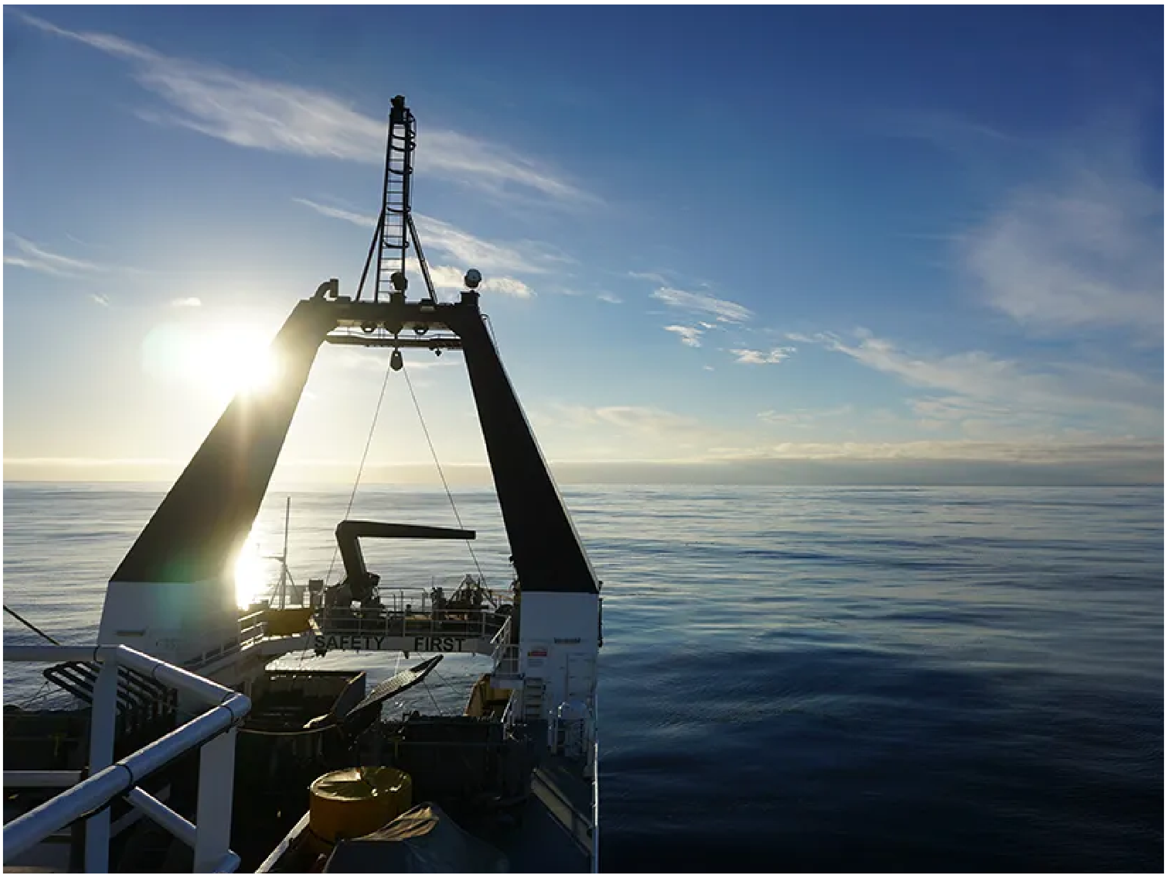

View of New Zealand's Canterbury coast from the R/V *Tangaroa* during the MARCAN program's April 2017 controlled-source electromagnetic survey. The MARCAN program seeks to fill a knowledge gap on the role of groundwater in shaping geological features at the continental margins. Credit: Susi Woelz

At various times during Earth's history, long periods of low temperatures, popularly known as ice ages, were characterized by expanding glaciers and falling sea levels. Vast areas of land that had previously been underwater were exposed to the atmosphere. This new land not only provided a habitat for land plants and animals (and early humans) but also hosted vast terrestrial groundwater systems that extended offshore.

Researchers have proposed that this offshore groundwater could have been an important agent in the formation of continental margins and their canyons. However, scientists have struggled to quantify a definitive link between submarine landscape forms and groundwater processes. The main challenges to solving these problems include a lack of mechanistic understanding of erosion and weathering caused by groundwater and limited information on offshore groundwater architecture and dynamics. To address this problem, scientists must understand how groundwater flowed when the sea level was as much as 120 meters lower than it is today and whether groundwater seepage was an effective erosive process.

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MARCAN, a 5-year European Research Council–funded project that launched in January 2017, addresses the role of offshore groundwater in the formation of submarine landforms at continental margins. Driven by the principle that topographically driven meteoric groundwater is an important geomorphic agent, MARCAN’s multiscale approach involves characterizing offshore groundwater systems in unprecedented detail and placing these systems into the framework of advanced continental margin geomorphic evolution models.

The project results are expected to guide future investigations of offshore groundwater systems, add a new dimension to continental margin research, and better reveal some of the most widespread and significant landforms on Earth. The MARCAN project’s direct mapping of offshore aquifers could be applied to improving offshore groundwater assessment techniques. Some possible applications of these assessments include tapping offshore freshwater as a source of drinking water, guiding offshore **carbon dioxide sequestration** efforts, and exploring for **mineral resources** and petroleum.

Groundwater's Unexplored Role at Continental Margins

Scientists have debated the role of groundwater seepage in geomorphology on land, particularly in the past decade [e.g., *Lamb et al.*, 2006; *Pelletier and Baker*, 2011]. In comparison, the significance of groundwater in submarine landscape development has hardly been addressed at all [e.g., *Johnson*, 1939; *Orange et al.*, 1994; *Paull et al.*, 1990; *Robb et al.*, 1981]. The link between groundwater processes and landscape form remains controversial and poorly quantified, largely because of the paucity of process-based observations and the simplistic assumptions underlying experimental and numerical analyses of groundwater processes.

As a result, groundwater erosion and weathering processes remain unquantified in terms of mechanisms, rates, and resulting morphologies, which inhibits our ability to reconstruct landscape evolution by groundwater seepage. This deficiency is particularly true for continental margins, where our understanding of the geomorphic efficacy of groundwater is limited by a poor understanding of offshore groundwater systems and the terrestrial bias of groundwater geomorphic studies.

Offshore Groundwater Dynamics

> ***Gaps in our knowledge arise mainly from a lack of appropriate offshore data and limited geophysical and geochemical investigations of offshore groundwater.***

Topographically driven meteoric recharge (TDM), a combination of rainfall recharge and topographically driven flow (water flowing downhill under gravity), is the most important source of groundwater recharge in terrestrial landscapes. TDM is also likely a very important driver of offshore groundwater systems in continental margins. The characteristics and dynamics of modern TDM offshore groundwater systems are poorly constrained, however. Also, many basic questions related to geometry, distribution, flow characteristics, and fluxes are still waiting to be addressed [e.g., *Moore*, 2010]. These gaps in our knowledge arise mainly from a lack of appropriate offshore data and limited geophysical and geochemical investigations of offshore groundwater.

For 80% of the **Quaternary period**, sea levels were much lower than they are today, partly because expanding glaciers locked up water in their ice masses. During these times, vast sections of the continental shelf were exposed, and coastal water table gradients were steepened, increasing topographically driven flow from inland aquifers to the sea and locally giving rise to freshwater springs [*Faure et al.*, 2002].

The capacity of TDM recharge to establish extensive water tables and generate massive groundwater fluxes across the continental shelf and slope was significantly higher during the majority of the last 2.6 million years than it is today [*Groen et al.*, 2000]. Current and past continental margin morphology and processes can thus be understood only in terms of a framework in which past sea levels were lower and TDM groundwater systems extended farther offshore. Understanding the architecture, history, and dynamics of TDM offshore groundwater systems has thus emerged as a new scientific frontier of critical value to seafloor geomorphology.

The MARCAN Project

MARCAN brings together the fields of geology, geomorphology, geochemistry, geophysics, hydrogeology, and engineering to address the hypothesis that TDM groundwater plays a key role in the geomorphic development of passive continental margins. This research project is led by the Marine Geology and Seafloor Surveying group of the University of Malta, with partners at the GEOMAR–Helmholtz Centre for Ocean Research Kiel in Germany, New Zealand's National Institute of Water and Atmospheric Research (NIWA), and the New Mexico Institute of Mining and Technology in Socorro.

The objectives of MARCAN are as follows:

- define the characteristics and dynamics of offshore TDM groundwater systems by determining their 3-D geometry and evolution in response to sea level changes

- assess whether TDM groundwater is an important geomorphic agent in continental margins by quantifying the rates and controls of groundwater weathering and erosion at the outcrop scale and determining the conditions in which TDM groundwater can shape landscapes

Two study areas provide a context for MARCAN. The Canterbury Bight, off the eastern coast of the South Island of New Zealand, is an example of a sedimentary passive margin. The northeastern Maltese Islands in the central Mediterranean Sea are an example of a carbonate bedrock margin. We selected these areas because they are representative of the most prevalent continental margin types globally and because they are comprehensively covered by good-quality baseline data (e.g., multibeam sonar, reflection seismics, and well data).

An Expedition to New Zealand

New Zealand's Canterbury margin is a unique site for investigating offshore groundwater systems in detail. It hosts one of the shallowest offshore groundwater reservoirs globally, and Integrated Ocean Drilling Program (**IODP**) Expedition 317 collected a wealth of borehole data in this region in 2009 and 2010 [*Post et al.*, 2013].

We collected marine controlled-source electromagnetic (CSEM) data along a total length of some 300 kilometers during the 4-week TAN1703 expedition on board R/V *Tangaroa* in April 2017 (Figure 1). We used a seafloor-towed electric dipole-dipole system to measure the subseafloor resistivity distribution, which can be related to porosity and pore water salinity changes.

Fig. 1. (a) Three-dimensional view of the South Island of New Zealand, compiled using data from NIWA and Land Information New Zealand, showing the location of Site U1353 (IODP Expedition 317) and the data acquired during MARCAN's TAN1703 oceanographic expedition. Red lines show seafloor-towed CSEM survey tracks, and the dotted gray polygon outlines the spatial coverage of multibeam echo sounder data, subprofiles, 2-D multichannel seismics, CTD casts, drop camera, and sediment coring. (b) Schematic of the CSEM system, which consists of a 100-meter-long electrical transmitting dipole (TX) and four electrical receiving dipoles (R1–R4) at offsets of 150, 275, 400, and 650 meters, respectively. A cable, attached to a weighted "pig," tows the system along the seafloor. The pig is equipped with electronic components, including a CTD sensor that measures seawater electrical conductivity, an indicator of water salinity.

To further constrain the groundwater model, we collected a comprehensive grid of **multibeam echo sounder** data, subbottom profiles, and 2-D multichannel seismic reflection data. These data will serve as the basis of a 3-D geological model. We used conductivity-temperature-depth (CTD) casts and a drop camera to locate and sample freshwater seeps, and we used piston coring to obtain pore water samples and measure the geologic and hydraulic properties of seafloor sediments.

To Malta and Beyond

We are planning a similar expedition for the Maltese Islands in autumn 2018. We will use data acquired during the New Zealand and Malta expeditions to develop 3-D numerical models of the study areas. These models will help us to estimate groundwater characteristics (e.g., extent, salinity, residence time, and flow rates) and simulate changes in these characteristics due to sea level fluctuations. On the basis of these estimates, we will perform laboratory experiments using seabed samples to simulate groundwater erosion and weathering [e.g., *Morz et al.*, 2007] and derive geomorphic rate laws for seepage weathering and erosion at the fine scale.

We will combine these rate laws with published models of canyon erosion and slope stability to develop advanced continental margin evolution models that include a groundwater flow component. Comparison of these model results with field data will allow us to determine if, and under which conditions, TDM groundwater is an effective geomorphic process in continental margins.

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MARCAN represents a unique opportunity to address long-standing and fundamental questions in continental margin geomorphology and hydrogeology, but its outcomes also have a strong applied value. Offshore groundwater systems are clearly of interest as a source of drinking water and **pollution**. What’s more, efforts involving seafloor engineering and carbon dioxide sequestration, as well as mineral resource and petroleum exploration, have an interest in past fluid migration histories. MARCAN will contribute essential baseline data, scientific knowledge, observational tools, and quantitative models that will assist the management of offshore natural resources and refine geohazard assessments.

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