MARCAN PROJECT
KEY OUTCOMES

MARCAN was a 5 year research project that investigated the role of offshore freshened groundwater (OFG) in the geomorphic evolution of continental margins.

MARCAN was a Starting Grant project supported by the European Research Council. It started in January 2017 and was led by Aaron Micallef.

The main outcomes of the MARCAN project are divided into two:

PHASE 1 - Characteristics and dynamics of offshore freshened groundwater systems

PHASE 2 - Role of offshore freshened groundwater in seafloor geology

MARCAN

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This project has received funding from the European Research Council (ERC) (Grant Agreement No 677898 (MARCAN)) under the European Union's Horizon 2020 Research and Innovation programme.

PHASE 1: Characteristics and dynamics of offshore freshened groundwater systems

1. Offshore freshened groundwater (OFG) review

Why? Establish the general characteristics and controlling factors of OFG occurrence, identify major knowledge gaps, and propose strategies to address them.

How? Global literature review and database compilation.

What? OFG has a global volume of 1 × 10^6 km^3; it mainly occurs within 55 km of the coast and down to a water depth of 100m. The majority of OFG was deposited when sea level was lower than today and is hosted in sandy sub-seafloor layers. Key knowledge gaps, such as the extent and function of OFG, and the timing of their emplacement, can be addressed by a range of geochemical, geophysical, and modelling approaches.

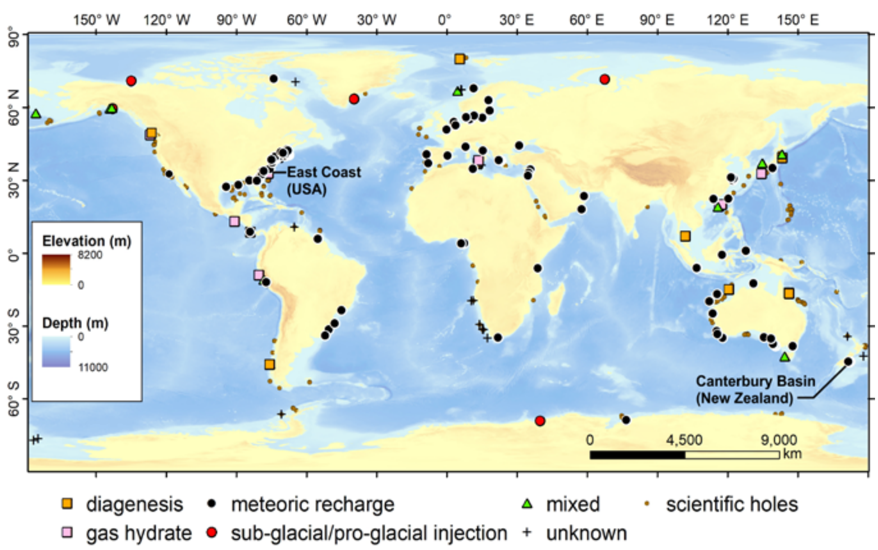

Figure 1 *Map of OFG records and emplacement mechanisms.*

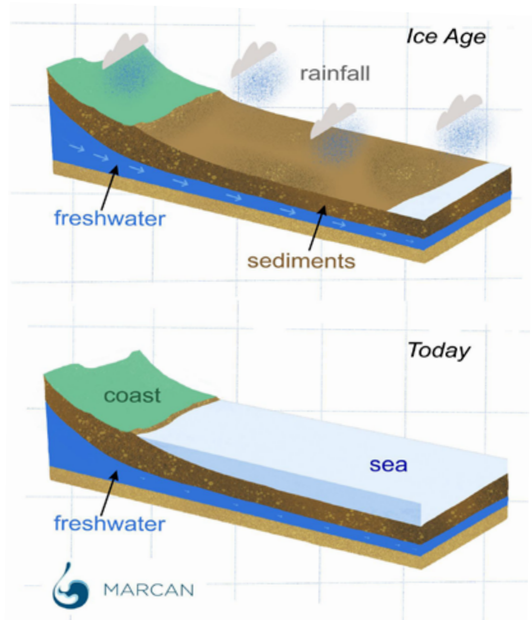

Figure 2 *Illustration of OFG emplacement mechanism offshore New Zealand.*

Micallef, A., Person, M., Berndt, C., Bertoni, C., Cohen, D., Dugan, B., et al. (2021). Offshore freshened groundwater in continental margins. Reviews of Geophysics, 59, e2020RG000706.

Expedition team

2. OFG in New Zealand (siliciclastic margin)

Why? To constrain the characteristics, origin and controls of the Canterbury Bight OFG system, offshore of New Zealand.

How? Various types of data such as controlled-source electromagnetic (CSEM), seismic reflection and borehole data, and groundwater modelling, were integrated to quantitatively characterise a previously unknown OFG system.

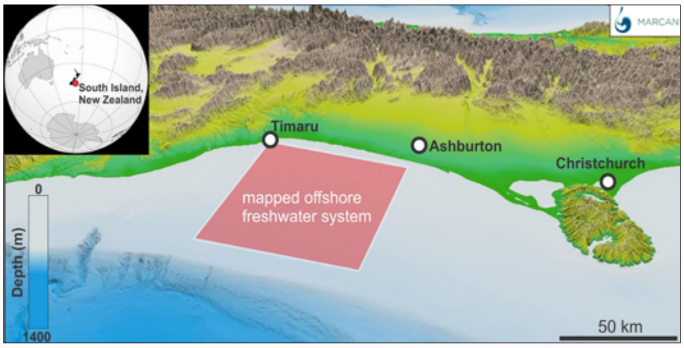

Figure 3 *Study area offshore New Zealand.*

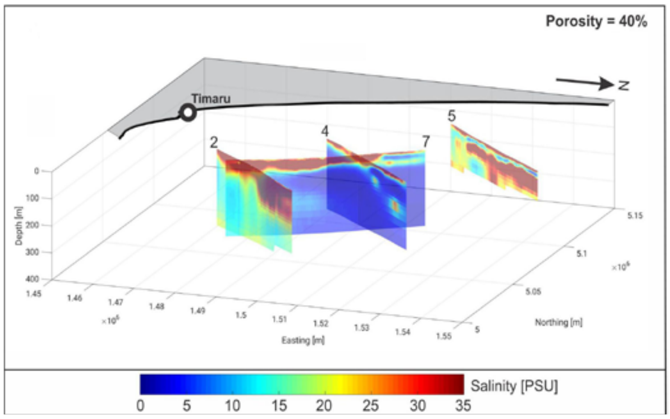

Figure 4 *Model of estimated sub-seafloor pore water salinity.*

What? Data integration is a powerful approach to quantitatively characterise an extensive OFG system (200 km³) in 3D, provide information on its emplacement during lower sea levels in the last 300,000 years, and document along-shore variability in OFG salinity.

Micallef, A., Person, M., Haroon, A., Weymer, B. A., Jegen, M., Schwalenberg, K., et al. (2020). 3D characterisation and quantification of an offshore freshened groundwater system in the Canterbury Bight. Nature Communications, 11, 1372.

Further reading on the connection between offshore and terrestrial aquifers along the Canterbury coast:

Weymer, B. A., Wernette, P. A., Everett, M. E., Pondthai, P., Jegen, M., & Micallef, A. (2020). Multi-layered high permeability conduits connecting onshore and offshore coastal aquifers. Frontiers in Marine Science, 7(903).

Figure 5 *RV Tangaroa, research vessel used for New Zealand expedition.*

Figure 6 *Fieldwork along the Canterbury coast.*

3. OFG in Malta (carbonate margin)

Why? To map freshened groundwater offshore the Maltese Islands, and to identify the factors governing its emplacement.

How? By using a combination of geophysical and lithological data with numerical groundwater modelling.

What? A potential OFG body is identified offshore the SE coast of Malta. Groundwater modelling suggests that this groundwater was deposited during lower sea levels and preserved in fine-grained units. This study demonstrates that OFG may be found offshore limestone coastline in dry climates, which are common in the Mediterranean region.

Expedition team

Haroon, A., Micallef, A., Jegen, M., Schwalenberg, K., Karstens, J., Berndt, C., et al. (2021). Electrical resistivity anomalies offshore a carbonate coastline: Evidence for freshened groundwater? Geophysical Research Letters, e2020GL091909.

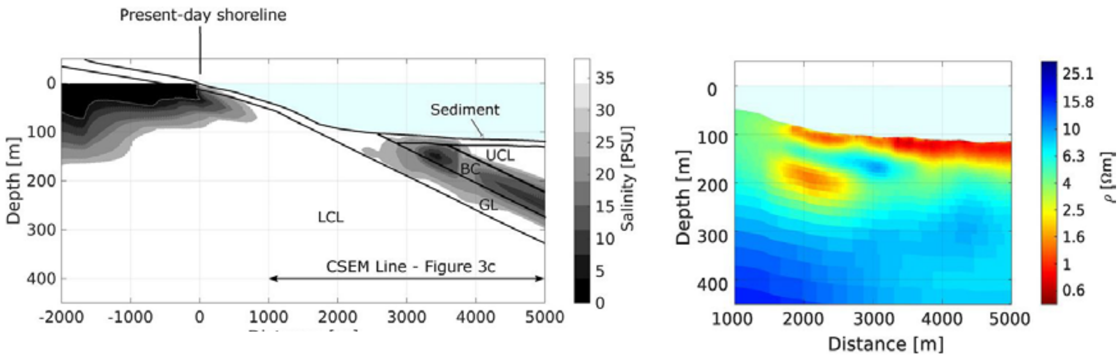

Figure 7
Comparison of resistivity model derived from CSEM (right) with groundwater modelling results (left) for a profile along the SE coast of Malta.

Figure 8 *RV Hercules, research vessel used for Malta expedition.*

4. Evolution of the onshore-offshore groundwater system in the Maltese Islands

Why? To reconstruct the evolution of the onshore-offshore groundwater system during the past 200,000 years, and predict its evolution in response to future climate-related changes.

How? 2D and 3D groundwater models

What? The Maltese onshore-offshore groundwater system is relatively dynamic, with 23% of groundwater being preserved as sea level rose in the last 18,000 years. At present the estimated volume of OFG is 1 km^3, which could potentially provide an alternative supply of potable water to the Maltese Islands for 75 years. A 30% decrease in groundwater recharge predicted in the coming 100 years will diminish OFG extent by 38% and onshore groundwater volume by 16%.

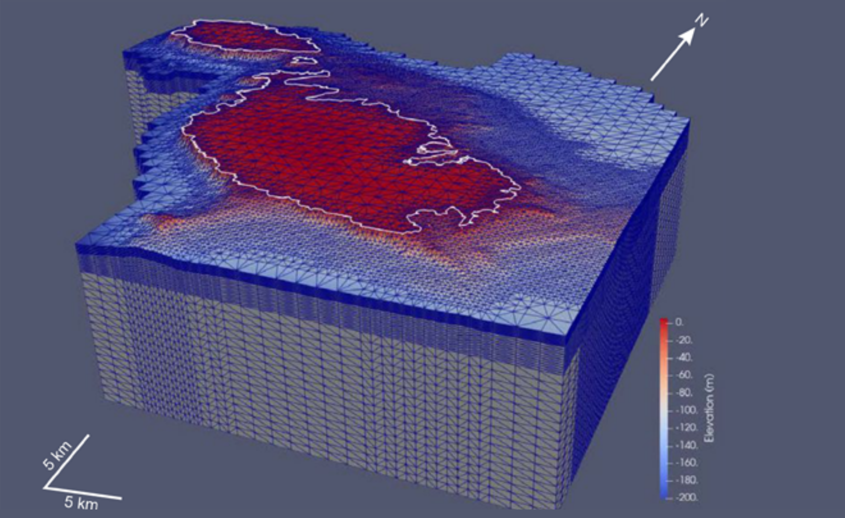

Figure 9 3D numerical model domain.

De Biase, M., Chidichimo, F., Micallef, A., Cohen, D., Gable, C., Zwinger, T., 2023. Past and future evolution of the onshore-offshore groundwater system of a carbonate archipelago: The case of the Maltese Islands, central Mediterranean Sea. Frontiers in Water, 4.

De Biase, M., Chidichimo, F., Maiolo, M., & Micallef, A. (2021). The Impact of Predicted Climate Change on Groundwater Resources in a Mediterranean Archipelago: A Modelling Study of the Maltese Islands. Water, 13(21), 3046.

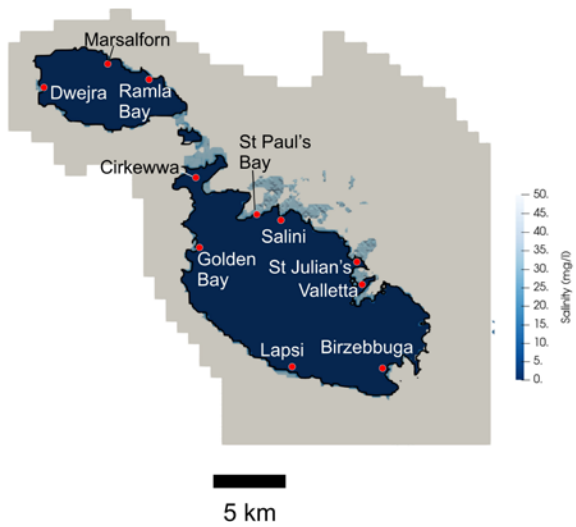

Figure 10 Predicted OFG distribution offshore the Maltese Islands.

PHASE 2: Role of OFG in seafloor geology

5. Salt leaching by groundwater flow and its impact on seafloor stability

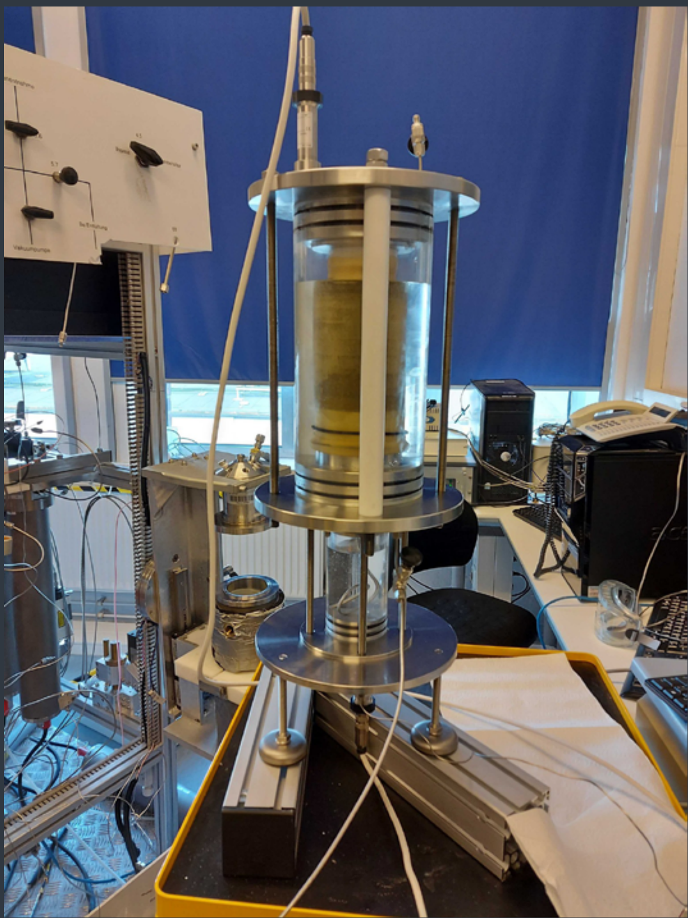

__Figure 11__ Experimental set up.

Why? To measure changes in the geotechnical properties of seafloor sediments due to salt leaching, and assess the implications of these changes on the stability of continental margins.

How? Flushing experiments, 2D numerical models.

What? We document a 50% decrease in the cohesive strength of seafloor sediments after leaching, as well as a decrease in its shear strength, bulk density, and moisture content, which is similar to that reported for subaerial quick clays undergoing salt leaching. When applied to a theoretical submarine domain 300 m wide by 100 m high, we estimate that salt leaching can trigger slope failure when the thickness of the flushed layer is >3.5 m or when the slope gradient is >3°. Salt leaching by OFG flow merits consideration as a potential mechanism destablising submarine sedimentary slopes.

Saadatkhah, N., Kassim, A., Siat, Q. A., & Micallef, A. (2023). Salt leaching by freshwater and its impact on seafloor stability: An experimental investigation. Marine Geology, 455, 106959.

6. OFG and mechanical instabilities in continental margins

Why? To assess whether OFG and its evolution during a glacial cycle can generate the pore pressures required to trigger mechanical instabilities in the seafloor.

How? Numerical simulations of groundwater flow and slope stability using conceptual models and evolving stratigraphy, for siliciclastic and carbonate margins.

What? Conceptual model results show that mechanical instabilities by OFG flow are most likely to occur in the outer shelf to upper slope, at or shortly before the Last Glacial Maximum sea-level lowstand. Models with evolving stratigraphy show that OFG flow is a key driver of pore pressure development and instability in carbonate margins. In siliciclastic margins, OFG flow plays a secondary role in preconditioning the slope to failure. OFG likely played a more significant role in carbonate margin geomorphology (e.g. Bahamas, Maldives) than currently thought.

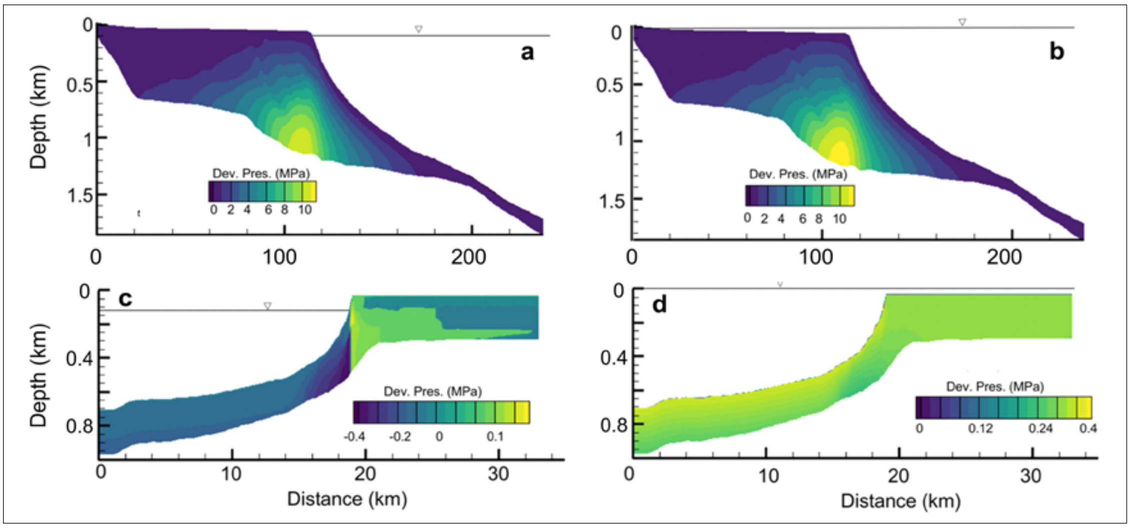

Figure 12 *Computed deviatoric pore pressures for the siliciclastic margin at the (a) Last Glacial Maximum and (b) present-day. Computed deviatoric pore pressures for the carbonate margin at (c) Last Glacial Maximum and (f) present-day.*

Micallef, A., Person, M., Gupta, S., Saadatkhah, N., Camille, A., Gratacós, Ò., 2023. Can Offshore Meteoric Groundwater Generate Mechanical Instabilities in Passive Continental Margins? Journal of Geophysical Research: Earth Surface, 128(3), e2022JF006954.

Micallef, A., Averes, T., Hoffmann, J., Crutchley, G., Mountjoy, J. J., Person, M., et al. (2022). Multiple drivers and controls of pockmark formation across the Canterbury Margin, New Zealand. Basin Research, 34(4), 1374-1399.

7. The geometry of seafloor erosional landforms formed by OFG flow (siliciclastic margin)

Why? To delineate the characteristics of seafloor landforms generated by OFG flow and seepage during a glacial cycle, and to identify their key controls.

How? 3D landscape evolution modelling.

What? Flow and seepage of OFG can generate landforms in siliciclastic margins in the presence of buried channels. Depth of the shelf-break controls the type, location and timing of landform formation. Width and depth of the buried channel affect the size of the landform, but not its type.

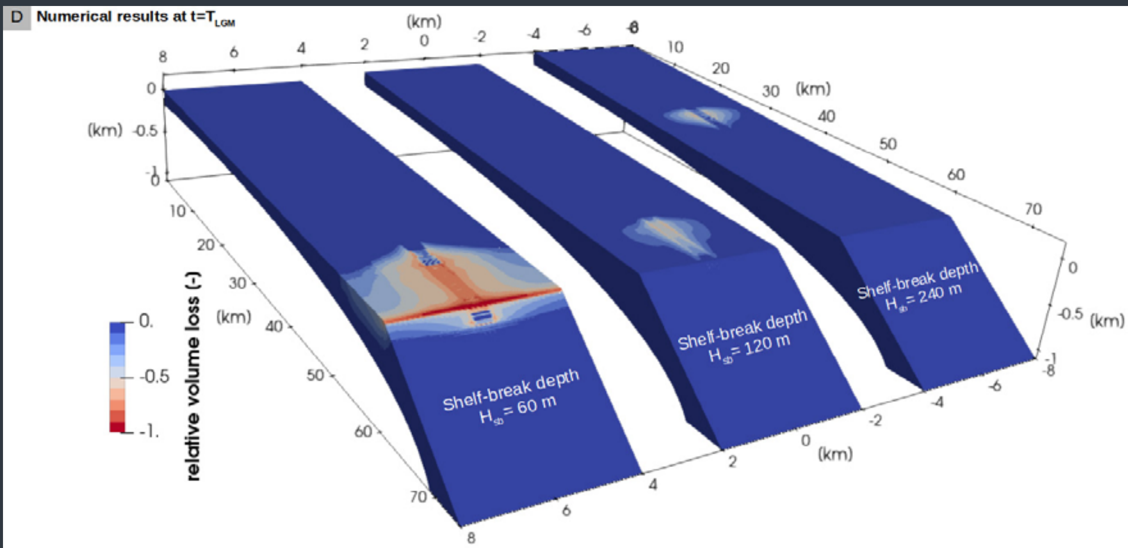

Figure 13 *Estimated sediment loss from a siliciclastic margin by OFG flow and seepage for different shelf break depths.*

Gupta, S., & Micallef, A. (in review). Characteristics and controls of erosional landforms formed by offshore groundwater flow in siliciclastic continental margins.

8. The geometry of seafloor erosional landforms formed by groundwater flow (carbonate margin)

Why? To determine if and how groundwater seepage can drive the formation of box canyons in submarine carbonate escarpments.

How? Numerical modelling (Florida Escarpment as study area).

What? Box canyon formation is a significant process eroding carbonate escarpments. Box canyons can initiate and retrogressively evolve by groundwater seeping via joints, which causes a reduction in rock strength due to fluid pressure and dissolution, resulting in periodic block failure at the canyon head. Since the key factors contributing to box canyon formation along the Florida Escarpment (i) an internal, density-driven fluid circulation system,(ii) limestone and dolomite outcrops that are susceptible to dissolution, and (ii) fabric (joints, faults) that enhances groundwater flow to the escarpment appear to characterize the Blake, Campeche and Malta Escarpments, the groundwater model for box canyon formation should be applicable to these escarpments as well.

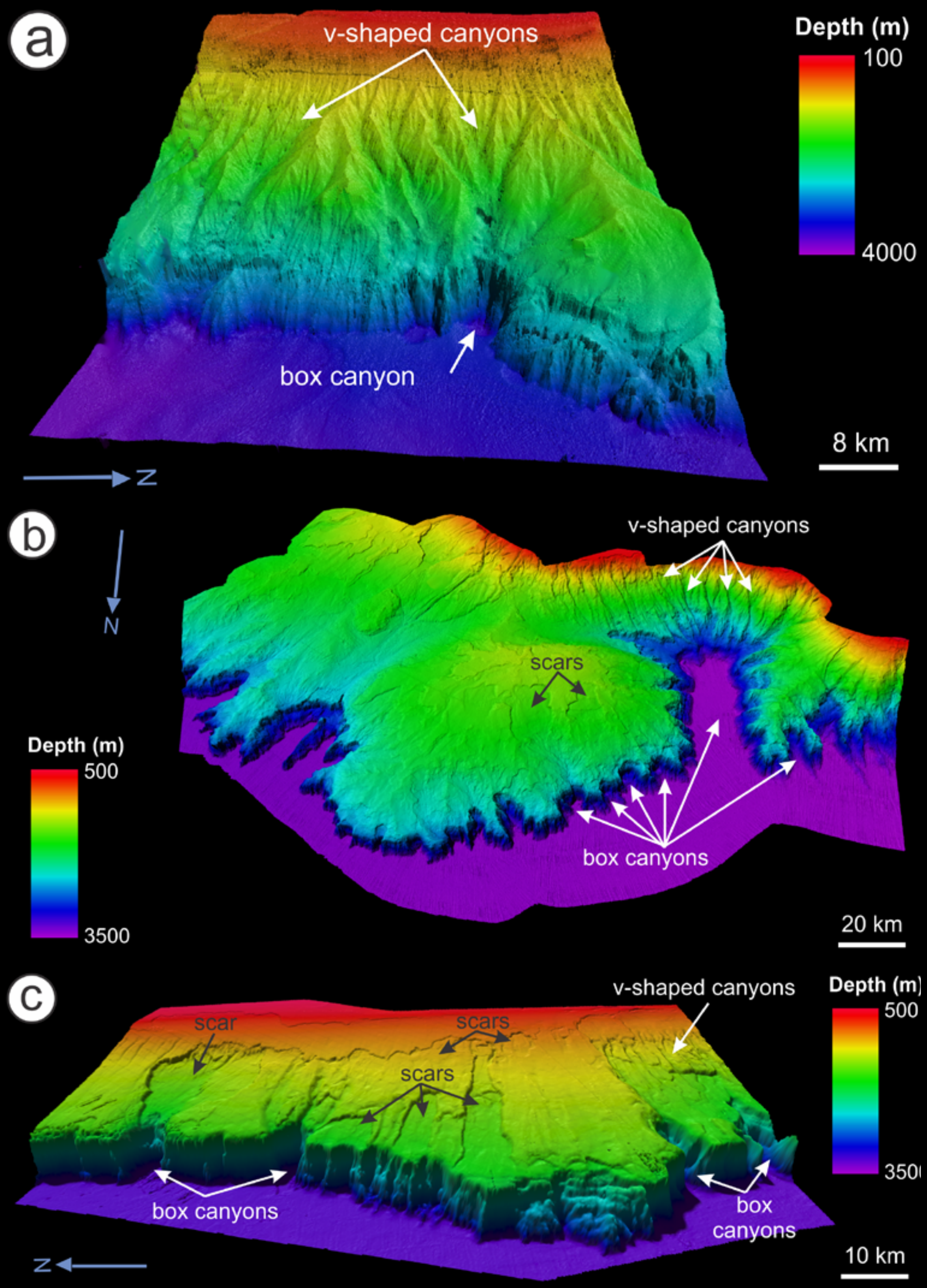

Figure 14 *3D renderings of bathymetry illustrating box canyons on the (a) Malta Escarpment, (b) Campeche Escarpment and (c) Florida Escarpment.*

Micallef, A., Paull, C. K., Saadatkhah, N., & Bialik, O. (2021). The role of fluid seepage in the erosion of Mesozoic carbonate escarpments. Journal of Geophysical Research: Earth Surface, 126(1), e2021JF006387.

9. Onshore analogs: groundwater flow and valley formation in unconsolidated siliciclastic sediments

Why? To constrain the temporal scale of gully formation by groundwater seepage and the influence of geological heterogeneity on their formation.

How? Field observations, luminescence dating, multi-temporal drone and satellite data, time domain electromagnetic data and slope stability modelling.

What? Gully formation is an episodic process associated to groundwater flow that occurs once every 227 d on average along the Canterbury coast, when rainfall intensities exceed 40 mm d^{-1}. Gullies can form at rates of up to 30 m d^{-1} via two processes, namely (i) the formation of alcoves and tunnels by groundwater seepage, followed by (ii) retrogressive slope failure due to undermining and a decrease in shear strength driven by excess pore pressure development. The location of gullies is determined by the occurrence of hydraulically conductive zones, such as relict braided river channels and possibly tunnels, and of sand lenses exposed across sandy gravel cliffs.

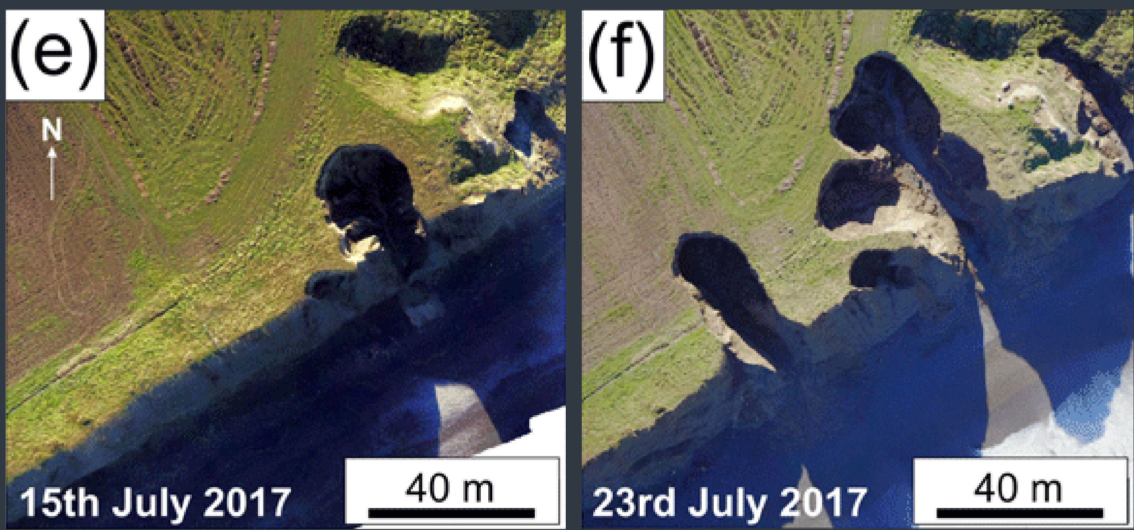

Figure 15 *Orthophotographs showing gully erosion by groundwater in a period of 8 days.*

Micallef, A., Marchis, R., Saadatkhah, N., Pondthai, P., Everett, M. E., Avram, A., et al. (2021). Groundwater erosion of coastal gullies along the Canterbury coast (New Zealand): A rapid and episodic process controlled by rainfall intensity and substrate variability. Earth Surface Dynamics, 8, 1-8.

10. Onshore analogs: groundwater flow and valley formation in bedrock

Why? To demonstrate that groundwater seepage can be the main driver of theatre-headed valleys (THV) formation in limestone.

How? Field observations, cosmogenic nuclide dating, multi-temporal drone and satellite data, ground penetrating radar, electrical resistivity tomography, and 3-D distinct element modelling.

What? The inferred erosion mechanisms associated to groundwater seepage entail (1) widening of joints and fractures by fluid pressure and dissolution and (2) creeping of an underlying clay layer, which lead to slope failure at the valley head and its upslope retreat. The location and width of THVs are controlled by the location of the master fault and the extent of the damage zone, respectively. The variability of seepage across the fault zone determines the shape of the valley head, with an exponential decrease in seepage away from the fault giving rise to a theatre-shaped head. Our model may explain the formation of THVs by groundwater in jointed, strong-over-weak chemical sedimentary lithologies, particularly in arid terrestrial settings.

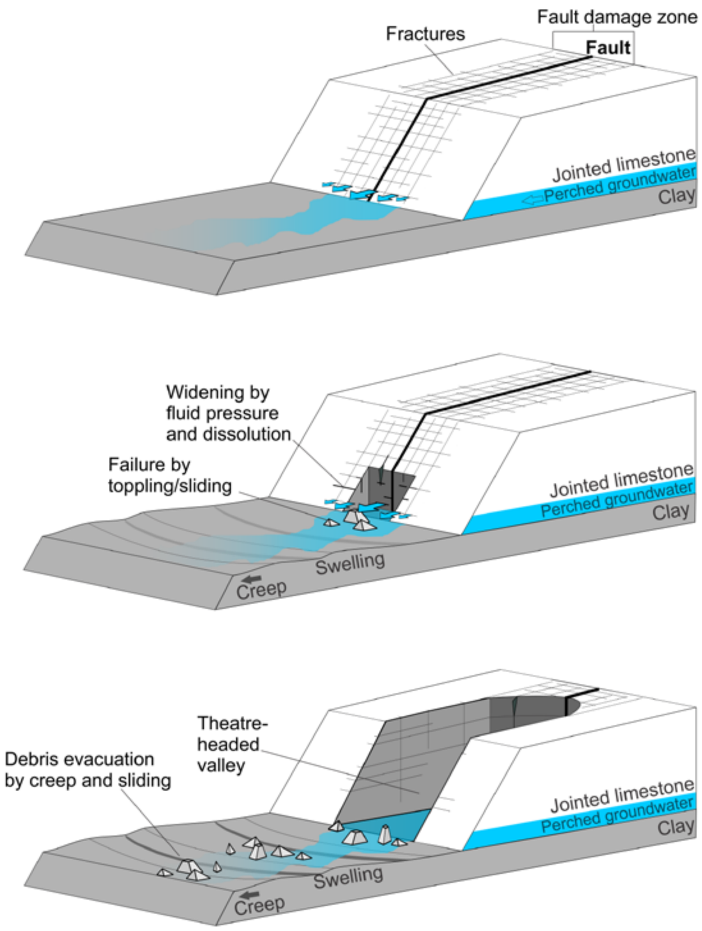

Figure 16 *Schematic model for the formation of theater-headed valleys in jointed limestone by groundwater flow.*

Micallef, A., Saadatkhah, N., Spiteri, J., Rizzo, E., Capozzoli, L., Pace, L., et al. (2022). Groundwater seepage is a key driver in the formation of theatre-headed valleys in limestone. Geology, 50(6), 686-690.

OFFSHOOTS FROM THE MARCAN PROJECT

OFF-SOURCE

Four year long COST Action CA21112 to determine whether OFG can be used as an unconventional water resource in coastal regions.

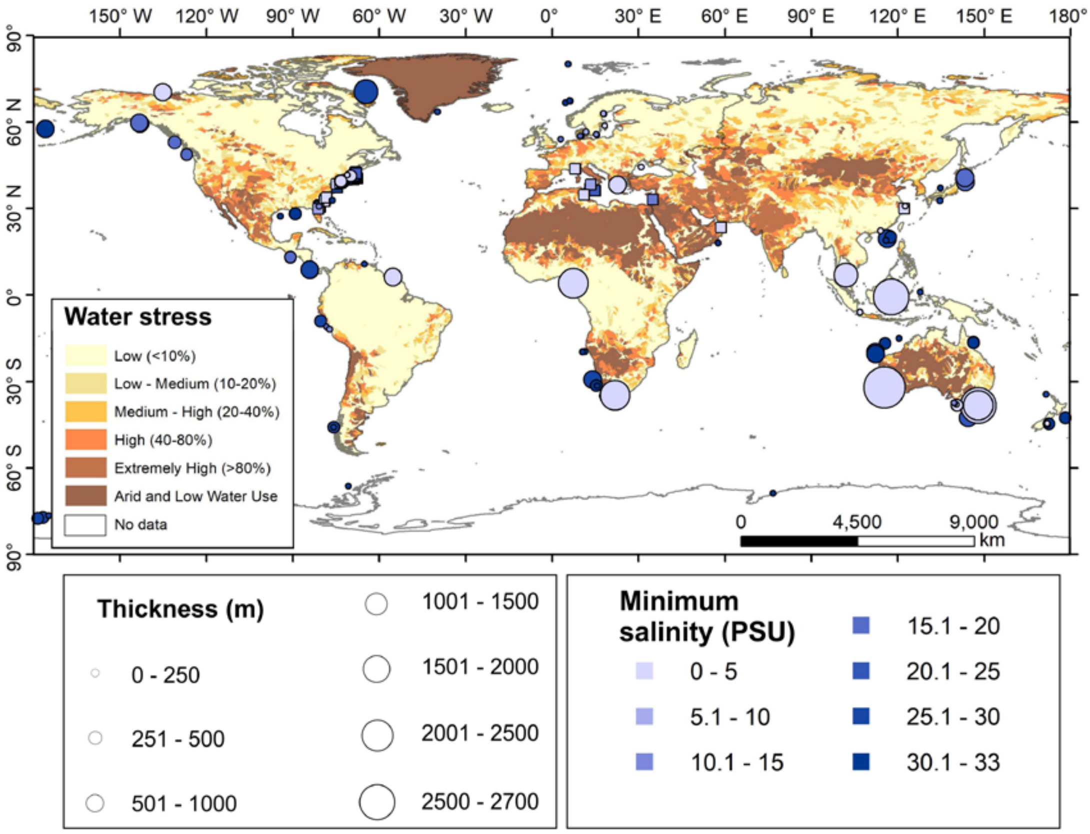

***Figure 17** OFG thickness and minimum salinity plotted on a global map of water stress.*

MGMTOFGR

MGMTOFGR is a 2-year project funded by the Malta Council for Science and Technology (MCST) and the Ministry of Science and Technology (MOST), China. The main objective is to develop an approach to determine the characteristics of OFG bodies by adapting existing geophysical instrumentation and software codes.

SWAN

SWAN is a 2-year project funded by the Energy and Water Agency during which a low-cost, modular controlled-source electromagnetic system will be developed to map submarine groundwater discharge and offshore groundwater resources.