

The coastal transition zone is an underexplored frontier in hydrology and geoscience

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We have better maps of the surfaces of Venus, Mars, and the Moon than of the Earth's seafloor. There is even less information available about the geologic structure below the seafloor. In particular, the transition zone deep beneath and crossing the coastline is a very poorly studied frontier resulting from limitations of technology and logistical barriers. Here, we point out the significance of this region for understanding fundamental geologic processes, geohazards, and especially coastal aquifers. One prominent example is the increasing awareness of the importance of groundwater exchange between land and sea. This Perspective defines the region beneath the coastal transition zone, or coastal white ribbon as an underexplored frontier, and highlights the need for characterization of this critical region to depths of tens of km. We discuss available geophysical methods and their limitations with coastal groundwater used as the primary illustration. Advances in geophysical and drilling technology, coupled with numerical modeling, are needed to enable better accounting of this poorly understood component of the geosphere.

The coastal transition zone is a gradational boundary^{1–3} comprising an elusive information gap spanning the onshore to shallow-water offshore region^{4,5}. Herein referred to as the coastal white ribbon, it is the zone near the coast in which data are not available (Fig. 1). It is one of the most challenging environments of the solid Earth system to study³ because water depths in nearshore areas are too deep for remote sensing from aircraft and satellites, but too shallow for deep-sea and ocean geophysical and drilling technologies. This relative inaccessibility has prohibited continuous data coverage across and beneath the seafloor. The region contains, amongst many intriguing targets, the transition from continental to oceanic crust^{6,7}. As an unexplored frontier⁸, we cannot yet grasp its full importance for certain fundamental Earth processes.

This Perspective first highlights several examples that identify the coastal white ribbon as an important frontier for a variety of research endeavors related to tectonics, hydrocarbon exploration, geohazards and coastal hydrogeology. In each case geophysical imaging complemented by scientific drilling is envisioned to play a primary role. We then focus on the connections between onshore-offshore aquifers as an illustration of the important need for white ribbon characterization. We discuss some current challenges and propose possible solutions in

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Fig. 1 What is the coastal white ribbon? The coastal white ribbon spans the transition between land and sea; it is herein defined as the nearshore shallow water region below which there exists a paucity of data constraining deep structure and processes. The image shows breaking waves resembling a white ribbon in the nearshore zone at Padre Island National Seashore, Texas, USA (Photo credit: B. Weymer. 29 November, 2013).

developing and/or adapting existing exploration geophysical and drilling technologies and integrating them with advanced subsurface process modeling. The paper concludes with a motivation for future research with the aim of developing capabilities to seamlessly bridge the transition from land to sea.

Tectonics

Tectonic interactions occur at plate boundaries often between continental and oceanic crust located in seismogenic zones. There has been a modest number of recent onshore-offshore seismic tomography studies that probe the tectonic structure beneath the coastal white ribbon. For example, an amphibious seismic tomography study was conducted across the Cascadia subduction zone⁹ comprising an array of onshore seismometers and offshore ocean-bottom seismometers. Shore-crossing teleseismic travel-time data were recorded and used to obtain starting models for asthenospheric-level mantle tomography. The travel-time dataset enabled the mapping to ~50 km depth of the first-order lateral heterogeneity of the ocean-continent transition caused by elevation and crustal thickness differences. In an active-source seismic study of cratonic structure, four lines spanning the coastal zone between northern China and the Bohai and South Yellow seas were acquired and analyzed by Liu et al.¹⁰. The amphibious lines each comprised land stations and ocean bottom seismometers. The resulting velocity models mapped deep crustal and lithospheric structure across the ocean-continent transition to ~50 km depth. While deep structure beneath the coastline was mapped in both studies, it is important to recognize there are always essential differences between onshore and offshore instrumentation that results in the presence of a distinct seam in measurements across shorelines.

Hydrocarbon exploration

Oil and gas exploration has long been conducted on the continental shelves of passive margins, including offshore Texas and Louisiana, USA. Despite decades of extensive data collection by petroleum companies, a white ribbon at the Gulf of Mexico is shown as the paucity of investigations nearer to the shore¹¹. While gravity and magnetic maps provide valuable albeit low-resolution shoreline-crossing structure of the basement rocks, the crustal structure of the shallow-water continental shelf including onshore-offshore continuity of pervasive salt structures (information of critical importance to hydrocarbon exploration) is difficult to ascertain due to the lack of geophysical technology that probes seamlessly across the shoreline. Eddy et al.¹² and

Miao et al.¹³ indicated that continental structure along the Texas-Louisiana coastline has influenced the opening of the Gulf of Mexico; however, a comprehensive shoreline-crossing interpretation is not possible since the two adjacent surveys are of different types, and more importantly, are disconnected at the coastal white ribbon.

Geohazards

Coastlines are subject to various geohazards including: inundation caused by extreme storms and sea level rise, volcanic activity, tsunamigenic earthquakes, and submarine landslides^{14–16}. Investigations of coastal geohazards would benefit from deep-probing geophysical data to assess potential threats to infrastructure on the seafloor and along the coast. A particularly dangerous coastal geohazard is that of a catastrophic volcanic event, highlighting the need for white ribbon characterization to better understand slope stability. Potential hazards caused by flank collapse at Mt. Etna, Italy have been recently investigated¹⁷. A shore-crossing structural assessment was achieved through a combination of state-of-the-art microbathymetry and continuous seafloor geodetic surveys. Extending this work, Klein et al.¹⁸ combined openly available high-resolution bathymetry and topographic grids to create shore-crossing digital elevation models of a number of volcanic islands around the world. While these studies expose current challenges in integrating onshore-offshore surficial topography/bathymetry, a more daunting geohazard assessment is seamlessly mapping deep geologic structures beneath the coastal white ribbon.

Coastal hydrogeology

Henceforth, for definiteness we focus on the application of geophysical, drilling and modeling techniques based on coastal hydrogeology as the prime example of the need for white ribbon characterization, although each of the foregoing application areas, and others, are of comparable significance. In hydrogeology, the lack of deep subsurface information beneath the coastal white ribbon impedes an accurate accounting of the partitioning and volume transfers between terrestrial groundwater and sub-ocean reservoirs¹⁹. Herein we must differentiate between groundwater that discharges directly into the ocean as submarine groundwater discharge (SGD) and groundwater that remains stored underground beneath the coastal zone. Central to the latter is the role of the hydrostratigraphy, a continuum of strata of varying grain sizes ranging from clay to gravel deposits of different thickness and extent. Active groundwater flow is restricted to the more permeable layers when these have inlets and outlets that allow recharge and discharge, but groundwater may also be virtually stagnant in confined regions or low-permeability strata²⁰. Recent numerical modeling suggests that mid-shelf offshore freshened groundwater (OFG) reservoirs^{21,22} offshore the New Jersey, USA coast may be laterally compartmentalized by downward fingering of seawater^{23,24}. Imaging the full vertical extent of the seawater's pathways is one of the challenges for deep-probing hydrogeophysics. Speaking more broadly, knowledge is lacking about the groundwater salinity distribution below continental shelves, as well as information about the (dis)connectedness of low-salinity groundwater bodies between the on- and offshore.

Defining the deep coastal white ribbon

We concern ourselves with the connection between onshore and offshore aquifers located at depths below the reach of presently-used geophysical techniques (Fig. 2). An OFG body is defined as a zone of lower salinity groundwater that is enclosed between layers of more saline groundwater²¹. The OFG's beneath the coastal white ribbon are important to study because of their potential as an unconventional resource²⁵. It is advantageous to understand

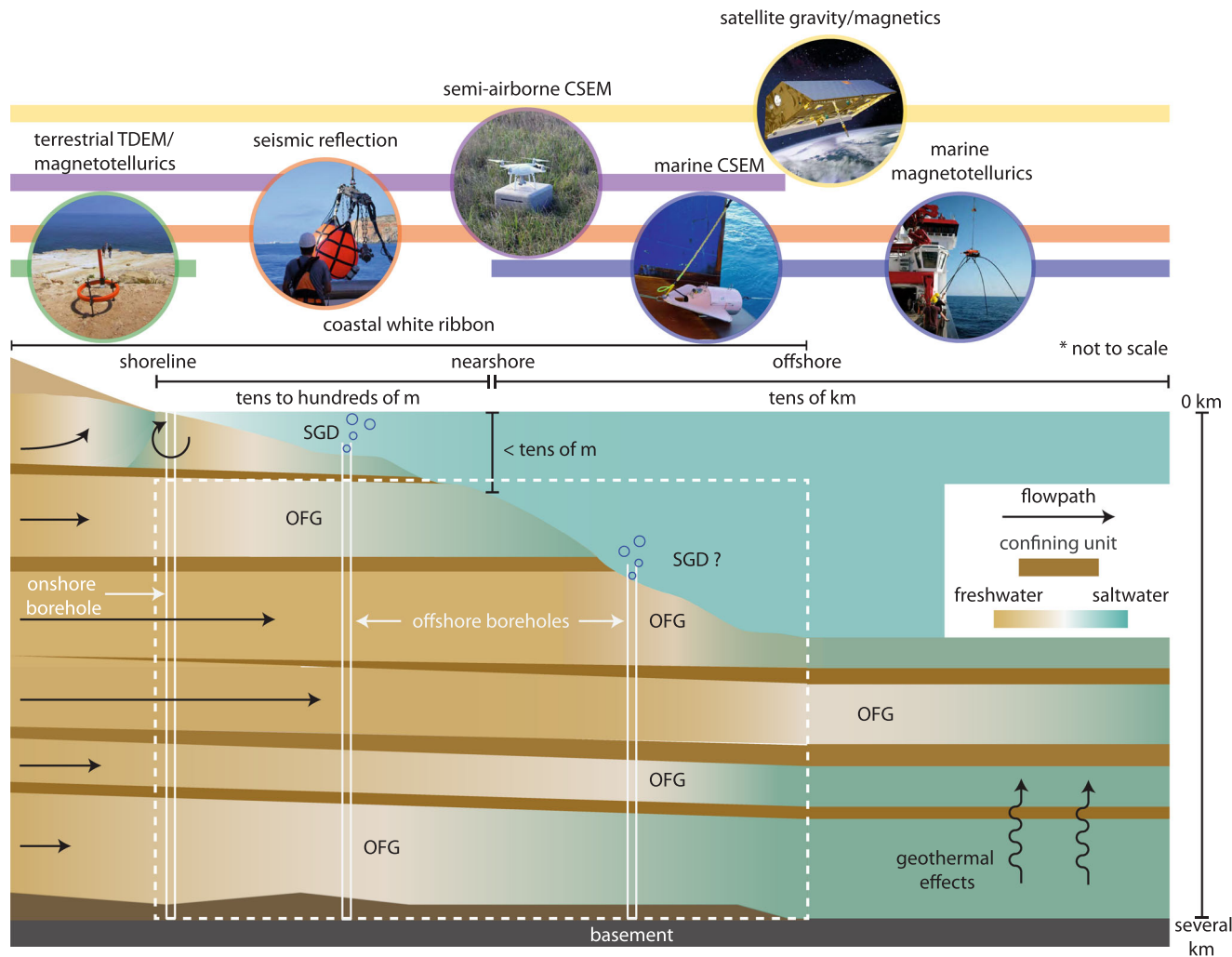


Fig. 2 Geophysical methods connecting onshore-offshore groundwater systems. Conceptual diagram depicting multi-layer groundwater reservoirs and their respective simplified fluid migration pathways beneath the coastal white ribbon. Offshore freshened groundwater and submarine groundwater discharge are abbreviated (OFG) and (SGD), respectively. The area of interest for deep exploration geophysics, boreholes, and groundwater modeling in shallow coastal waters is outlined by the white dashed lines. Existing geophysical methods for deep groundwater exploration crossing the white ribbon and their respective zones of coverage are indicated by the colored bars intersecting the middle of each image. All images in the bubbles are owned by the authors except the satellite gravity/magnetics image “Courtesy NASA/JPL-Caltech”.

how groundwater may be actively discharging to the continental shelf farther offshore, or how it is actively discharging to the shallow seafloor via upward migration within the white ribbon itself.

The relevant target zones of interest include the embayment and shelf scale confined aquifers discussed by Bratton²⁶. For clarity, the embayment scale includes the first confined submarine aquifer and its terminus at the continental shelf rise, whereas the shelf scale spans the width and thickness of the aquifers throughout the entire continental shelf. Following the nomenclature of Bratton²⁶, we define the coastal white ribbon zone to be that which ranges in the vertical from the top of the uppermost confining layer downward to the top of the geological basement, as shown by the dashed lines in Fig. 2. Note that this definition is primarily based on the application of the various deep-probing techniques that we highlight in this Perspective. We envision the landward boundary of the coastal white ribbon to be the present shoreline and the seaward boundary to be the vertical line outboard of which marine data can be acquired using large research vessels. This is an operational demarcation that can change as technology evolves. We intentionally are not concerned with

aquifer systems crossing the nearshore where SGD occurs²⁷, as this region can be explored by existing technologies (albeit challenging). Although shallow unconfined aquifers in the nearshore can already be covered by existing methods, they cannot probe deeper than ~100 m. Thus, we need techniques to achieve seamless interpretation in both lateral and vertical directions.

The dimensions of onshore and offshore aquifers located beyond the zone of interest, if not already known, can be mapped using existing geophysical methods, primarily electromagnetic (EM) and seismic techniques. However, the geometry of putative deep, nearshore pathways (conduits) spanning the terrestrial and marine domains remains unexplored. It is worthwhile to appreciate the great challenge of imaging the flux of groundwater across the boundaries beneath the white ribbon region, which is governed by forcing mechanisms whose effects span many scales of both space and time²¹. Recent EM studies investigating onshore-offshore fluid migration pathways suggest their aquifer geometries are highly variable, ranging from a few meters to hundreds of meters wide and extending to depths of a few meters to hundreds of meters^{28,29}. Resistivity maps derived from EM surveys offshore New Zealand, Malta, and Hawai'i, USA provide

evidence that groundwater conduits in clastic, carbonate, or volcanic settings are principally governed by geological heterogeneities that cause complex three-dimensional subsurface bulk resistivity anomalies^{28–32}.

The most recent estimate of the global volume of OFG²¹ is $1 \times 10^6 \text{ km}^3$. This large number underscores the substantial challenge with respect to understanding the groundwater budget beneath the coastal white ribbon. Many large OFG's are located beneath the maximum depth of investigation of conventional terrestrial, marine, airborne or amphibious hydrogeophysical methods. Geophysical technologies are also prone to a range-to-resolution tradeoff meaning that vertical resolution decreases with increasing depth of investigation. How then can we account for this elusive part of the global hydrologic cycle, keeping in mind the high spatial resolution that is necessary for imaging aquifers that may only be tens of meters thick in some locations?

Existing deep exploration geophysical techniques

Geophysical methods suited for groundwater (and other deep-probing crustal) investigations³³ are generally restricted to depths of <1 km and for the most part are designed for terrestrial use, resulting in a limited capability of imaging deep beneath the coastline (Fig. 2). Commonly used near-surface terrestrial techniques such as ground penetrating radar^{34,35}, electrical resistivity^{36–38}, and various frequency and time-domain induction-based methods^{28,39–42}, have contributed to our understanding of shallow (depths from 10's to 100's of meters) coastal substructure. Looking deeper, large scale inductive EM methods involving a loop⁴³ or a grounded dipole⁴⁴ transmitter can penetrate to ~3 km or more.

In the offshore region, towed marine controlled-source electromagnetic (CSEM) systems configured for nearshore exploration^{29,32,45,46} achieve a depth of investigation not much greater than ~500 m beneath the seafloor²⁹. With the possible exception of emerging coastal semi-airborne EM systems^{40,41,47}, the lack of overlap between onshore and offshore geophysical methods has prohibited seamless coverage of geological structure beneath the coastal white ribbon. Semi-airborne methods use inductive currents that have limited resolution of resistive layers

in conductive environments. In Table 1, we discuss several geophysical studies that have provided some indications of deep onshore-offshore hydraulic connectivity.

Geophysical horizons for onshore-offshore mapping

Several geophysical techniques have the potential to be adapted for deep investigations beneath the coastal white ribbon (Fig. 2). In the context of hydrogeology, the uppermost confined aquifers crossing the white ribbon can in principle be imaged by existing marine CSEM and semi-airborne EM techniques^{29,48–51}. Practically, however, marine CSEM is limited in its lateral coverage because the shallow water depths approaching the coast prohibit safe navigation by conventional research vessels. Towing a ~1 km long array of instrumentation in a nearshore setting is a hazardous operation. A few surface-towed CSEM systems have been deployed from smaller coastal vessels, allowing surveying into shallow waters of a few meters, close to the surf zone. Surveying within the surf zone itself is impractical from a boat and probing to depths of more than several tens of meters has not been demonstrated for surf-zone acquisition systems such as unmanned surface vehicles, motorized kayaks, benthic crawlers, etc.

Fully airborne inductive-EM methods, although capable of traversing the entire white ribbon, have different challenges related to their lack of sensitivity to resistive layers and signal attenuation caused by conductive seawater. Additionally, flight paths are generally restricted to sparsely populated coastal areas. The deeper confined aquifers extending to the top of basement, in principle, could be investigated by seismic⁵², gravity⁵³, magnetics⁵⁴, MT⁵⁵, or some combination thereof. The shared limitation of these deep-probing techniques is the lack of resolution necessary to resolve potentially thin (tens of meters thick) aquifers. MT data are known to be strongly affected by the strong lateral electrical contrast at the shoreline⁵⁶. Furthermore, gravity data respond to mass distributions and magnetics to magnetization distributions, neither of which are directly informative of prevailing hydrogeological conditions. Seismic, MT, gravity and magnetics nevertheless play useful complementary roles in determining the large-scale continental shelf architecture. The optimal geophysical method, or combination of methods, will

Table 1 Existing geophysical methods for deep onshore-offshore coastal probing along with representative studies.

Geophysical method	Application	Approx. depth of investigation
Magnetotellurics (MT)	Gustafson et al. ⁴⁶ recorded 100-Hz offshore MT responses, probing deep beneath the coastal white ribbon. Blatter et al. ⁸¹ jointly inverted offshore MT/CSEM data.	60 km
Marine CSEM	Attias et al. ²⁹ describe marine CSEM data offshore Hawai'i aimed at connecting terrestrial to offshore freshwater reservoirs. The survey vessel was navigated close to the shoreline.	500 m
Semi-airborne CSEM	Abd Allah et al. ⁸² describe the time-domain GREATEM ⁴⁸ configuration wherein a terrestrial grounded electric dipole source is deployed and airborne receivers measure magnetic field variations along flight lines crossing the white ribbon. A similar semi-airborne system SATEM ⁴⁹ exists but has not been used for deep-probing white ribbon studies. The frequency-domain semi-airborne system DESMEX ⁸³ for terrestrial applications achieves depth penetration of several km.	0.4–2.0 km
Seismic reflection	Seismic reflection has been used to map deep aquifers beneath the coastal white ribbon ⁵² in the North Atlantic and Mediterranean, offshore Florida, and elsewhere. Offshore seismic data are sometimes tied to onshore boreholes ⁸⁴ . Seismic imaging provides structural boundaries and lithology which can be used to convert marine-CSEM resistivity maps into subsurface fluid distributions ⁸⁵ .	3 km
Borehole	IODP Expedition 313 ⁸⁶ drilled three shallow-water boreholes in ~35 m water depth specifically for OFG exploration with core recovery to ~500 m depth.	500 m
Satellite-based	Gravity data have mapped offshore geology on the continental shelf including the ocean-continent boundary ⁵³ important to the petroleum industry. The sensitivity of gravity data to deep-white ribbon hydrogeology is insufficient to map offshore aquifers and/or establish onshore connectivity. Similar remarks hold for magnetic data ⁵⁴ for which the sensed property is magnetization.	basement

Box 1 | Combining coastal hydrogeophysics with groundwater modeling

Geophysical imaging of the coastal white ribbon can reveal important aspects of its geological structure and hydrogeological architecture, but reveals little about the dynamic processes that are critical to its contribution to the global hydrologic cycle. Groundwater modeling is an indispensable tool to further the understanding of offshore groundwater systems because it can incorporate information from geophysical imaging with solutions to the physical hydrodynamic equations that govern both groundwater storage and fluxes deep within the coastal white ribbon. Despite the widespread use of groundwater models for understanding onshore coastal groundwater resources and seawater intrusion⁸⁷ and for quantifying SGD offshore, progress in groundwater modeling to capture the dynamics of OFGs is constrained by the white ribbon information gap, as in geophysics. The earliest OFG modeling studies shed light on the importance of sea-level variations and glaciations in the formation of fresh groundwater bodies⁸⁸. More recently, modeling has illustrated the role of geological heterogeneity to drive fresh groundwater from beneath the continents to far offshore, resulting in active OFG systems and irregular patterns of SGD across the seafloor⁸⁹.

Geological heterogeneity as an OFG driver breaks the paradigm that sea-level lowstands are a prerequisite for the formation of fresh groundwater reserves below the continental shelf. Recent global compilations of offshore sedimentary systems^{19,90} have shown that both heterogeneity and sea-level changes influence OFG systems and the balance between these spatial and temporal drivers may be reserve-dependent. Modeling can help evaluate the persistence of OFG bodies, particularly in response to both onshore and offshore pumping^{91,92}. Additional modeling is needed that incorporates long-timescale, sea-level, and hydrologic changes as well as geologic complexity to understand more broadly the existence, functioning, and persistence of OFG systems.

So far, limitations on available data have restricted the development of groundwater modeling at the spatial scale necessary for understanding fully three-dimensional OFG systems. With parallelization of computer codes and improvements in computing power, in the near future three-dimensional modeling over long timescales should come within reach⁹³. Expanded computational power will allow quantitative testing of hypotheses, such as the one that states that the morphology of the exposed continental shelf land surface during sea-level lowstands controls the configuration of the groundwater flow systems that develop. Paleo-drainage networks also critically influence the flooding of the shelves during periods of sea-level rise, and thereby the salinization of groundwater. Three-dimensional modeling is expected to lead to insights into this phenomenon and many other dynamical processes of freshwater emplacement and preservation. Hydrological modeling can and has been used to simulate hydrologic processes over geologic timescales^{23-25,88}. In fact, that is one of the great strengths of adding a modeling component to observations - it is a means to test hypotheses about the evolution of a system over time in order to understand how the present conditions came to be, and then how the system may evolve in the future. Geophysical observations usually only provide a snapshot of present conditions, whereas hydrogeological models provide physics-based context. Further, the onshore-offshore hydrogeologic connectedness that can give rise to active OFG systems is inherently 3D; this has been shown with 3D modeling of onshore-offshore systems on small scales⁹⁴. As long as large-scale models remain two-dimensional representations, it remains unknown how 3D onshore-offshore connectedness affects the rate of freshening of subsurface fluids, the emplaced volumes, and the groundwater fluxes.

depend on the local/regional geologic setting and the size and depth extent of the hosted target(s) of interest.

Seismic reflection data can provide detailed geophysical constraints on the structural and stratigraphic configuration of deep coastal aquifer systems⁵². As opposed to the bulk electrical resistivity measurement of EM sounding, seismic reflections reveal interfaces between strata of different acoustic and elastic properties. While reflection seismic imaging can resolve deep subsurface structure with good horizontal and vertical resolution both in two and three dimensions⁵⁷, it does not discriminate the type or salinity of the pore fluid in the subsurface. Shore-crossing seismic tomography is a viable option for geophysical characterization beneath the coastal white ribbon, but the current protocol is to stitch together disparate onshore and offshore datasets^{9,10}. Spatial resolution is governed by the frequency content of the seismic source, the seismic velocity distribution, and the density of the seismic sources and receivers⁵⁸. As there is a trade-off between penetration and useful frequency content, a good target definition in advance of the survey is essential for making the best choice of seismic source. For imaging the top 1 km of the subsurface, vibroseis sources and explosives are used on land while airguns are used offshore⁵⁹. Both can provide seismic resolution of 1–5 m in the horizontal and vertical directions. Sub-bottom profilers may be used at the seafloor but only for very shallow targets in the uppermost 10–20 m.

While seismic imaging of both onshore and offshore structures is well established, seismic imaging beneath the coastal white ribbon in shallow waters is notoriously difficult, due in part to the presence of strong seafloor multiple reflections. At present, where feasible, custom-made solutions are required for each new setting. As a rule of thumb, a seismic source can easily be towed behind a small ship or barge⁶⁰. Therefore, shot coverage tends to be denser in the offshore part of a survey. A good example is P-Cable 3D seismic data acquisition that enables high resolution imaging^{61,62}. Data recording in the offshore domain is typically carried out

with streamers that are towed behind the source or geophones that are placed on the seafloor. In areas with strong tides, it is common to deploy the seismic receivers at low tide and acquire the seismic data at high tide, but this is obviously not an option for shorelines without a large tidal range such as the Mediterranean or Baltic Seas. As the quality of seismic imaging does not depend on the direction of the seismic travel path it is often useful to choose a seismic survey design with a denser recording network on land and a denser shot spacing offshore. Carefully designed seismic surveys beneath the white ribbon zone, while difficult, constitute the primary geophysical approach for constraining the geological background structure of confined aquifers and they will comprise an important basis for hydrological modeling and evaluation of other types of deep-probing geophysical data.

Technological needs and future research directions

Improved tools are needed to explore the connectivity of groundwater pathways, past, present, and future between deep terrestrial and offshore confined aquifers. Mapping geologic structure and salinity distributions with geophysical measurements reveals information about the location and overall geometry of coastal groundwater systems. This in turn informs how they function under hydrologic change including sea level change and pumping to better understand groundwater hydraulics and dynamics (see Box 1 for further details).

A key aspect to addressing the coastal white ribbon information gap is scientific drilling. The International Ocean Discovery Program's (IODP) mission-specific platform approach⁶³⁻⁶⁵ is an ideal vehicle for shallow water operations, but it is out of reach for the two flagship deep-sea drilling vessels - the JOIDES Resolution and Chikyu. There are considerable technological challenges to drilling in shallow coastal waters for deep (>0.5 km) targets. Many nearshore depositional environments host coarse-grained unconsolidated

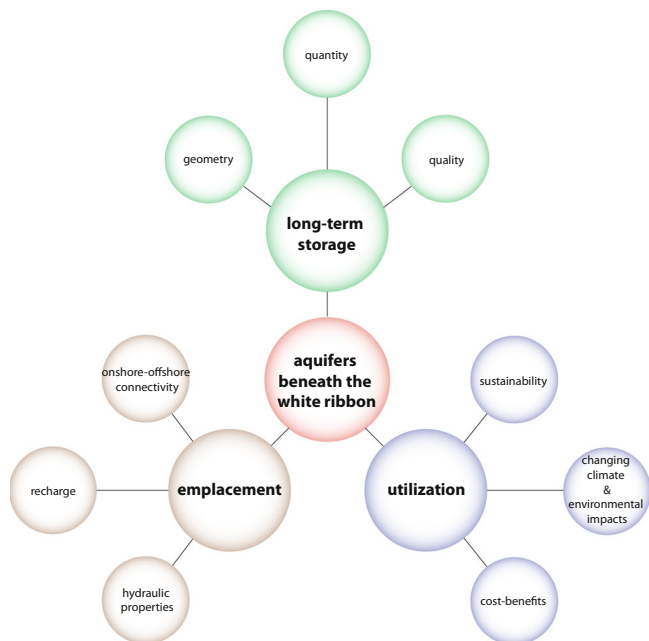


Fig. 3 Exploring deep coastal groundwater systems across space and time. Aspects of coastal aquifers that motivate future research. The three larger bubbles correspond to where does the water come from (emplacement), where is it now (long-term storage) and where is it going (utilization)? Note: similar diagrams can be drawn for other research applications (e.g., tectonics, hydrocarbons, geohazards) crossing the white ribbon.

sediments including interbedded gravels and sands that are problematic to drill with existing advanced piston coring technology. The question is whether deep sediment coring is possible in shallow waters and what drilling platforms are required, such as floating barges, jack-ups or lift boats.

Sediment coring into the coastal white ribbon and ideally installing Circulation Obviation Retrofit Kit (CORK)^{66,67} long-term subseafloor observatories could result in a step-change understanding of how OFG's function and the overall importance of connections between the onshore and offshore systems. However, the requisite shallow-water technology is not yet proven. Borehole information is a vital complement to geophysical data as it provides important constraints on sediment physical properties including; porosity, resistivity, and acoustic p-wave velocities. Similarly, core samples provide crucial data on interstitial water, microbiology, and headspace gas elements that in turn aide in determining the age and residence times of the water, distribution of downhole salinity, and nutrient concentrations.

Conservative and reactive tracers⁶⁸ can be valuable tools in evaluating the origin and functioning of OFG systems. This reinforces the impact of installing dedicated subseafloor borehole observatories through IODP drilling operations. Results from cross-hole conservative tracer experiments carried out in ODP Leg 168 and IODP Expeditions 301/327 boreholes along the Juan de Fuca Ridge have shed light into deep seafloor (depths ~300-500 mbsf) hydrothermal circulation^{69,70}. However, this kind of work also requires adapted technology for it to be extended into the white ribbon because of the difficulty of drilling deep boreholes in shallow waters.

Due to the inherent multi-disciplinary nature in coastal hydrogeological research, understanding the connections, storage and fluxes of groundwater beneath the white ribbon is likely to benefit from data collected by deep-probing geophysical and drilling technologies. A lack of data often forces groundwater

modelers to make simplified assumptions about the offshore groundwater salinity distribution (e.g. all groundwater is saline) that may not be in line with the more complex reality⁷¹. Researchers focused on either side of the coastline face similar challenges, but often approach solutions from different perspectives^{72,73}. It is important to bridge the information gap across and beneath the white ribbon to bring these two scientific communities together to expand the global inventory of deep coastal groundwater systems and model their dynamics and evolution in response to climate change⁷⁴ and possible future resource exploitation^{25,75-77}.

A number of research directions, in the context of coastal hydrogeophysics, stimulate cross-disciplinary efforts in geophysical imaging and modeling of groundwater systems beneath the white ribbon (Fig. 3). Some of these include, but are not limited to: (1) adapting existing and further developing geophysical tools to provide seamless shore-crossing data acquisition complemented by improved drilling capabilities; (2) advancing 3D groundwater modeling for quantifying the emplacement, dynamics, and evolution of deep coastal groundwater systems (see Box 1); and (3) developing common Earth models that integrate relevant datasets into a geospatial environment that can be easily accessed, updated, and understood across scientific disciplines¹⁴. Advances in these directions can, in principle, be applied to the other research applications outlined at the beginning of this Perspective. The research directions displayed in Fig. 3 are motivated by either strong scientific and/or societal needs offering opportunities for investigators working together to close the elusive information gap beneath the coastal white ribbon. For example, groundwater modelers can inform geophysicists of their imaging requirements with regard to geological heterogeneity and salinity distributions, whereas geophysicists can communicate with modelers to identify the most promising onshore-offshore systems to investigate. Although the characterization of the white ribbon will be built around collaborations between geophysicists, engineers, marine geologists and modelers, as illustrated above, there will be abundant opportunities for investigators in many other fields of coastal science and engineering. Improved mapping and modeling technologies will open windows into the unexplored region beneath the white ribbon that can then be studied in greater detail by geochemists and biologists in regard to the age, residence times, and quality of the water as well as characterization of the deep biosphere⁷⁸⁻⁸⁰, the microbial and benthic communities of which remain almost entirely unknown.

The coastal white ribbon remains a frontier that is largely unexplored due to logistical and technological challenges that prevent seamless coverage across the land-sea transition. Although strides are being made to bridge the information gap, most work to date has utilized interpolation between disparate datasets crossing the shoreline and/or has focused on the challenges associated with integrating terrestrial and marine datasets to map surface morphologic features³. In other words, we have only begun to scratch the surface, and a challenge moving forward is to characterize the deep (>0.5 km) white ribbon region with seamless data coverage. Improved technologies are needed to fill the blank slate lying deep beneath the coastal white ribbon.

Data availability

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Author contributions

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Competing interests

The authors declare no competing interests.

Additional information

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