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Geoelectrical signals of geologic and hydrologic processes in a fringing reef lagoon setting

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SUMMARY

Coastal groundwater may discharge into nearshore and offshore waters forced by terrestrial fluxes, controlled by local geology, and modulated by the hydrodynamics of littoral water. We investigated the electrical signature of these features with a dense, multiscale network of electrical resistivity tomography (ERT) surveys in the Muri Lagoon of Rarotonga, Cook Islands. The ERT surveys spanned from onshore to 400 m into the lagoon and used standard electrodes on land and across the foreshore, submerged electrodes in the shallow subtidal zone, and floating electrodes towed throughout the reef lagoon by a boat. ERT surveys on land mapped a typical freshwater lens underlain by a saltwater wedge, but with possible deviations from the classical model due to an adjacent tidal creek. Further inland, ERT surveys imaged a layer of lava flow deposits that is potentially a confining hydrogeologic unit; this unit was used to constrain the expected electrical resistivity of these deposits below the lagoon. ERT surveys across the intertidal zone and into the lagoon indicated fresh groundwater and porewater salinity patterns consistent with previous small-scale studies including the seaward extension of fresh groundwater pathways to the lagoon. Electrical resistivity (ER) variations in the lagoon subsurface highlighted heterogeneities in the lagoon structure that may focus submarine groundwater discharge (SGD) through previously unknown buried lava flow deposits in the lagoon. A transition to higher ER values near the reef crest is consistent with the ER signature of porosity reduction due to ongoing differential cementation of reef deposits across the lagoon. The imaged coastal hydrostratigraphic heterogeneity may thus control terrestrial and marine porewater mixing, support SGD, and provide the pathways for groundwater and the materials it transports into the lagoon. This hydrogeophysical investigation highlighted the spatial heterogeneity of submarine coastal geology and its hydrogeologic control in a reef lagoon setting, but is likely to occur in many similar coastal settings. Ignoring geologic complexity can result in mischaracterization of SGD and other coastal groundwater processes at many spatial scales.

1. Introduction

Coastal communities often rely on limited freshwater resources that are vulnerable to changes in groundwater storage and contamination (White and Falkland, 2010; Bailey and Jenson, 2013). Coastal groundwater systems respond to these perturbations over multiple timescales controlled in part by aquifer properties (Michael et al., 2005; Ferguson and Gleeson, 2012; Gonneea et al., 2013). Moreover, spatial heterogeneities in permeability and porosity, related to lithology and/or geologic history, can accentuate the effects of climate- or human-induced changes on groundwater availability and residence times for even large aquifers (Swarzenski et al., 2013). Thus, delineating coastal hydrogeologic structure, or hydrostratigraphy, can improve the characterization of groundwater flow and management of groundwater resources. Additionally, hydrostratigraphic complexities may control how coastal aquifers interact with marine ecosystems, transport solutes to coastal waters, and respond to perturbations such as climate change.

Electrical resistivity (ER) surveys have been used extensively in coastal settings to reveal groundwater dynamics and mixing with seawater (e.g., Zohdy and Jackson, 1969; Manheim et al., 2004; Breier et al., 2005; Day-Lewis et al., 2006; Swarzenski et al., 2006; Swarzenski and Izbicki, 2009; Cardenas et al., 2010; Henderson et al., 2010; Dimova et al., 2012; Befus et al., 2013). Many ER studies rely on assumptions of geologic homogeneity to interpret porewater salinity variations, or to interpret inconsistent ER anomalies as unexplained variability in geologic properties. However, subsurface geologic heterogeneity is ubiquitous in

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coastal environments, where structural, volcanic, erosional, and diagenetic processes shape and alter coastal geology (Moore, 2001; Montaggioni and Braithwaite, 2009; Evans and Lizarralde, 2011; Rankey and Garza-Perez, 2012; Ramalho et al., 2013). Time-lapse ER surveys remove some uncertainty when interpreting the results of coastal ER studies, as the changes measured in time-lapse ER surveys are predominantly from dynamic porewater salinity rather than changing subsurface geologic materials or their electrical properties (Ogilvy et al., 2009; Zarroca et al., 2011; Dimova et al., 2012; Befus et al., 2013; Misonou et al., 2013). But, even these surveys suffer from uncertainty associated with both the ER structure and the electrical boundary conditions in or over dynamic salinity water regimes (Day-Lewis et al., 2006; Henderson et al., 2010; Orlando, 2013). Thus, ER surveying always images the subsurface within an integrated geologic and hydrodynamic context, and the relative contributions of each to the measured ER signal must be acknowledged during interpretation.

As the ultimate goal of many coastal ER studies is to elucidate groundwater features, ER surveys are used to develop and test the reliability of groundwater models. However, insights into the hydrodynamic processes involved in submarine groundwater discharge (SGD) and porewater mixing within the subterranean estuary often arise through models that predominantly consider a homogeneous subsurface (e.g., Robinson et al., 2007; Vandenbohede and Lebbe, 2007; Gibbes et al., 2008; Xin et al., 2010; Konikow et al., 2013). Coastal ER results can compare favorably to shoreline groundwater simulations, but are typically based on the assumption of homogeneity (Henderson et al., 2010; Nakada et al., 2011). However, both geologic data (Moore, 2001; Emery and Myers, 2009; Ramalho et al., 2013) and geophysical surveys (Zohdy and Jackson, 1969; Evans and Lizarralde, 2011; Dimova et al., 2012; Misonou et al., 2013; Russoniello et al., 2013) document spatial heterogeneity across multiple spatial scales. Indeed, spatial variability in substrate properties and hydrodynamic conditions exist within the subterranean littoral zone and contribute to the magnitude of benthic fluxes (Santos et al., 2012b; Dose et al., 2014; Sawyer et al., 2013). In this study, we characterize coastal geologic heterogeneity with ER surveys in the context of a fringing reef lagoon system. These methods and results can help guide future SGD field studies and coastal groundwater flow models as they evolve to measure and incorporate different scales of heterogeneity.

We investigate the hydrostratigraphic framework of a reef in southeastern Rarotonga with comprehensive onshore and offshore electrical resistivity tomography (ERT) surveys and interpret the findings within the context of previous geologic and hydrologic studies. First, we briefly revisit related studies on Rarotonga that detected active fresh SGD at the same field site. We use a petrophysical model and the range of ER values corresponding to fresher porewater from the previous work to identify other areas where fresh groundwater may be present and volumetrically significant in the subsurface with the more extensive ERT network in this study. Next, we discuss the ERT surveys within the context of the local geology to understand the effects of spatial heterogeneity of the lagoon geology on the ERT results. We then explore the sensitivity and uniqueness of these ER results with synthetic simulations (i.e., forward models) to assess the reliability of our data and to guide the interpretations. Finally, we extend these results to elucidate potential heterogeneous geologic controls on groundwater pathways into any nearshore or reef system.

2. Study site

Rarotonga is a 67 km^2 volcanic island with a fringing reef located in the south-central Pacific Ocean (21.2°S 159.8°W) (Fig. 1a). The island was formed by basaltic eruptions $\sim$2 million years ago (Ma), experienced a brief volcanic hiatus, and then underwent a short period of late-stage volcanism (Thompson et al., 1998). Eroded and weathered basalts (1.1–2.3 Ma) now shape the rugged, mountainous interior of Rarotonga. A narrow rim (0.3–1.2 km) of alluvium and reef deposits surrounds the exposed volcanic rocks. Within this coastal plain, spring- and stream-fed wetlands form inland of beach-ridge deposits. During average flows, nearly all of the streams terminate in these coastal marshes and do not discharge directly to the coast (Waterhouse and Petty, 1986). The fringing reef crest ranges from 50 to 900 m offshore and sets the breadth of the shallow (<3 m) reef lagoon.

This study was conducted in the Muri area and Muri Lagoon on the southeast of Rarotonga (Fig. 1). Muri Lagoon is the widest portion of the lagoon surrounding Rarotonga (500–800 m) and contains the only lagoon islets. Both on and offshore, the local geology at Muri is complicated by the Raemaru phonolite flow deposit (1.1 Ma) that is exposed in the mountainous interior as well as the southernmost islet, Taakoka. The subterranean expression of the Muri Raemaru flow is unknown but may extend into the Muri Lagoon (Thompson et al., 1998). On land, the surficial geology consists of carbonate sand beach ridges, wetland sediments, and alluvial deposits (Moriwaki et al., 2006), which comprise a shallow aquifer system with groundwater flow towards the coast (Waterhouse and Petty, 1986). An ER sounding in north Muri detected volcanic bedrock at 13.7 m depth, potentially constraining the thickness of the coastal aquifer (Ricci and Scott, 1998). The geologic framework of the lagoon and near-beach environment addressed in this study has not been investigated in detail to our knowledge.

Previous hydrologic studies at Muri provide site-specific evidence of SGD into the reef lagoon. Many of the recent studies focus on the coastal environment near Parengaru Creek, a perennial creek that is tidally-affected until the main coastal road (Fig. 1b). Porewater sampling at the outlet of Parengaru Creek identified brackish porewater (<20 practical salinity units, PSU) extending 50 m into the lagoon with fresher porewater (<10 PSU) 10 m seaward of the high tide mark (Erler et al., in press). SGD also delivers significant amounts of reactive nitrogen into the lagoon (Erler et al., in press). Most of the saturated sediment was anoxic within 3 cm of the water table or sediment–water interface (SWI) (Cyronak et al., 2012). Along a nearby transect, an ERT survey imaged ER values > 1.5 Ωm over the first 10 m of the intertidal zone, where net groundwater discharge (up to 1 m d^{-1}) was also measured directly with both pressure and temperature measurements (Befus et al., 2013). Beyond quantifying groundwater dynamics at the coast, significant SGD fluxes (0.2–1.9 cm d^{-1}) into the Muri lagoon were calculated using radiogenic isotopes (Tait et al., 2013). Thus, the Muri Lagoon actively receives SGD, but the distribution and pathways of this SGD to the lagoon remain poorly constrained.

3. Electrical resistivity (ER) methods

Direct current ER surveys measure the electrical potential field generated by controlled electrical current sources. Earth materials have different electrical resistivity values as a function of chemical composition and porosity, and the bulk ER of subsurface materials can be significantly reduced by the low ER of ion-rich interstitial fluids (Telford et al., 1990). Disentangling the relative contributions of lithology and porewater in a measured ER signal relies upon petrophysical models. In sandy sediment or rock, the bulk ER (ρ_b) of the fluid and the matrix can be described using the empirical relationship (Archie, 1942):

$$\rho_b = \rho_f n^{-m} \quad (1)$$

incorporating ER contributions from the fluid resistivity (ρ_f) and the properties of the matrix through the porosity (n) and a cementation