Influence of the Last Glacial Maximum on New Jersey shelf offshore fresh groundwater reservoirs - investigating the role of geological heterogeneity
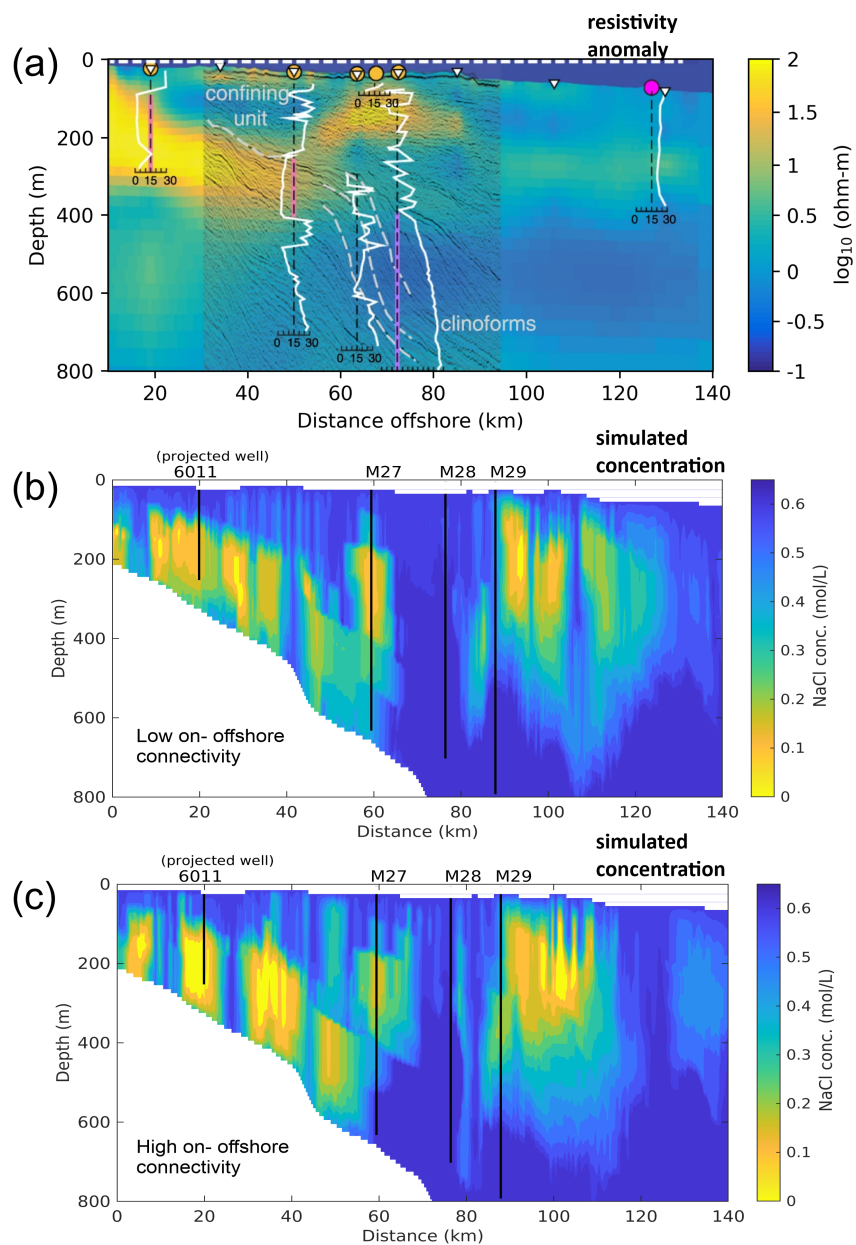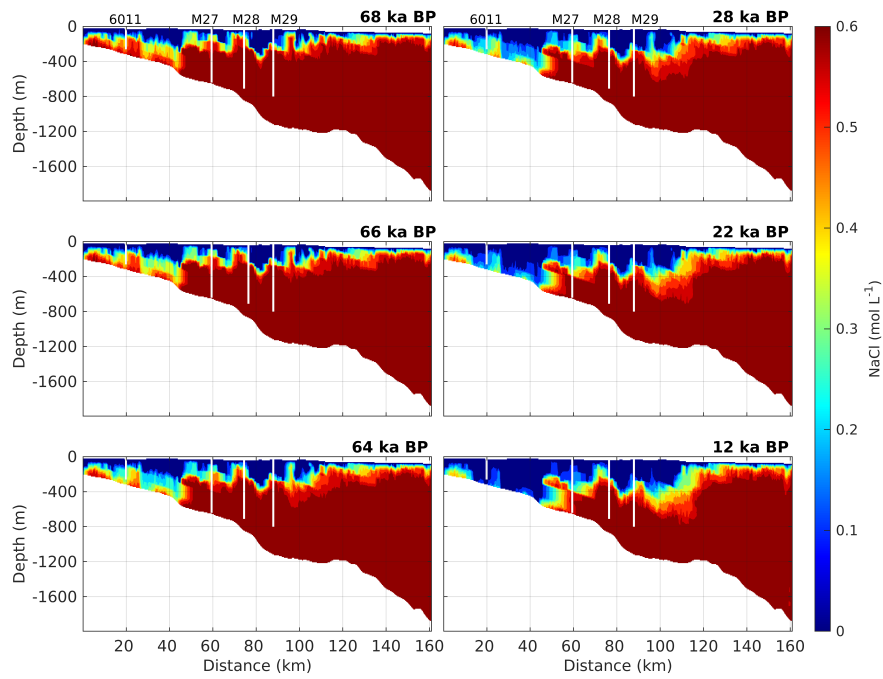
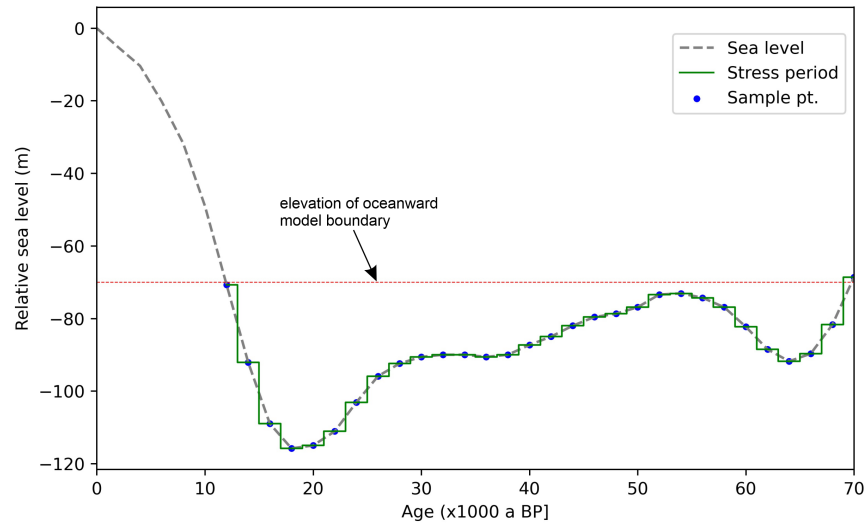Ariel T Thomas[1], Sönke Reiche[1], and Christoph Clauser[1]
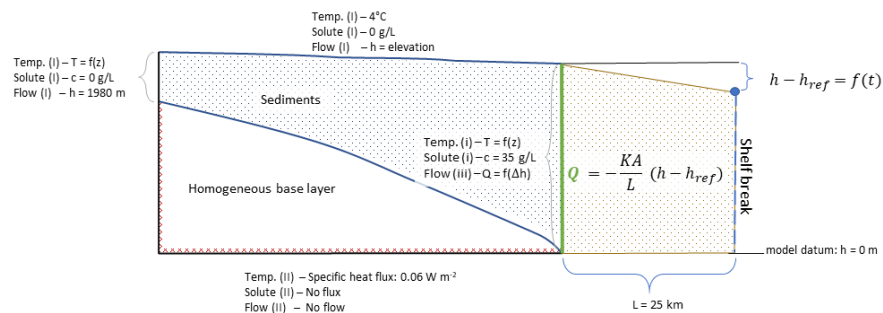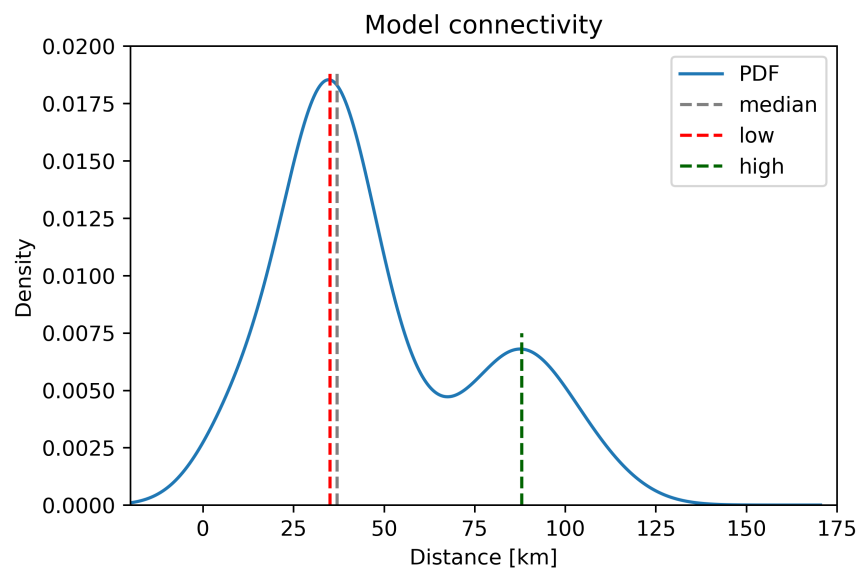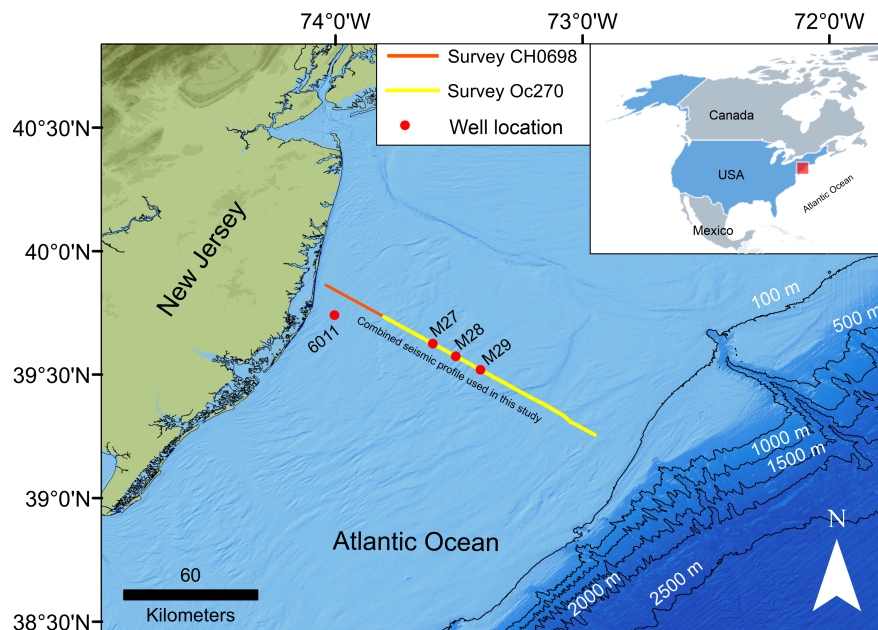
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Abstract

Offshore freshened groundwater reservoirs occur on continental shelves in several regions of the world. Their origins are an active area of research, however, models often rely on simplified geometrical representations of subsurface geology. The New Jersey shelf hosts an extensive multi-layered freshened groundwater system that previous paleo-reconstructions have not reproduced. In this numerical case-study, we aim to characterize the New Jersey shelf system in the context of a geologically representative heterogeneous model. Our model combines sequence stratigraphic interpretation of 2D depth migrated seismic lines and a stochastic facies distribution with petrophysical properties of four boreholes. We employ a stochastic approach to generate both high and low onshore-offshore connectivity scenarios. The study considers a 58 000-year recharge period for the subaerially exposed shelf transect, followed by the marine transgression from 12 000 years ago until today. The results show that the lowstand period drove sufficient freshwater emplacement that can explain most of the present-day observations. The highest rates of recharge occurred during the periods of most rapid sea-level fall. Simulated scenarios indicate that topographically driven flow of meteoric recharge via surface-connected pathways is the key emplacement mechanism. Surviving freshwater systems exhibit lateral variability in salinity due to downward fingering of saline pore fluid. Freshwater preserved from the Last Glacial Maximum may extend up to 100 km from the coastline. The results also suggest that cyclical flushing and re-salinization of shelf sediments during glacial-interglacial cycles is an asymmetrical process, promoting freshwater storage over geological time scales.

Model connectivity

Influence of the Last Glacial Maximum on New Jersey shelf offshore fresh groundwater reservoirs – investigating the role of geological heterogeneity

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Key Points:

- The Pleistocene sealevel lowstand provided sufficient conditions to freshen most of the mid-Miocene sediments on the New Jersey shelf.

- Onshore-offshore connectivity is not required to explain the mid-shelf freshened reservoirs.

- Downward fingering of saltwater via seafloor-connected pathways in the sediment column compartmentalizes the preserved freshwater system.

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19 geometrical representations of subsurface geology. The New Jersey shelf hosts an extensive multi-

20 layered freshened groundwater system that previous paleo-reconstructions have not reproduced.

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22 a geologically representative heterogeneous model. Our model combines sequence stratigraphic

23 interpretation of 2D depth migrated seismic lines and a stochastic facies distribution with

24 petrophysical properties of four boreholes. We employ a stochastic approach to generate both high

25 and low onshore-offshore connectivity scenarios. The study considers a 58 000-year recharge

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33 may extend up to 100 km from the coastline. The results also suggest that cyclical flushing and re-

34 salinization of shelf sediments during glacial – interglacial cycles is an asymmetrical process,

35 promoting freshwater storage over geological time scales.

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Plain Language Summary

Large volumes of freshwater have been found in sediments on continental margins worldwide. On-going research aims to explain their origins and potential resource viability. The area offshore New Jersey on the Central Atlantic coast of North America contains a complex freshwater reservoir system. We conducted simulations incorporating the existing field data to analyze the history of fluids in the subsurface from the last ice-age until today. Over this period, relatively low sea-level allowed previously salty regions of the subsurface to become flushed with freshwater. We examine the factors which influence the speed and extent of this process. The results show that large volumes of freshwater entered the subsurface at distances over 100 km from the current coastline. As the planet warmed and sealevel rose, complex layering of the rocks in the subsurface protected a portion of this freshwater from the salty ocean water. These offshore reservoirs may contain significant amounts of fresh groundwater and we need to improve our understanding of these complex systems.
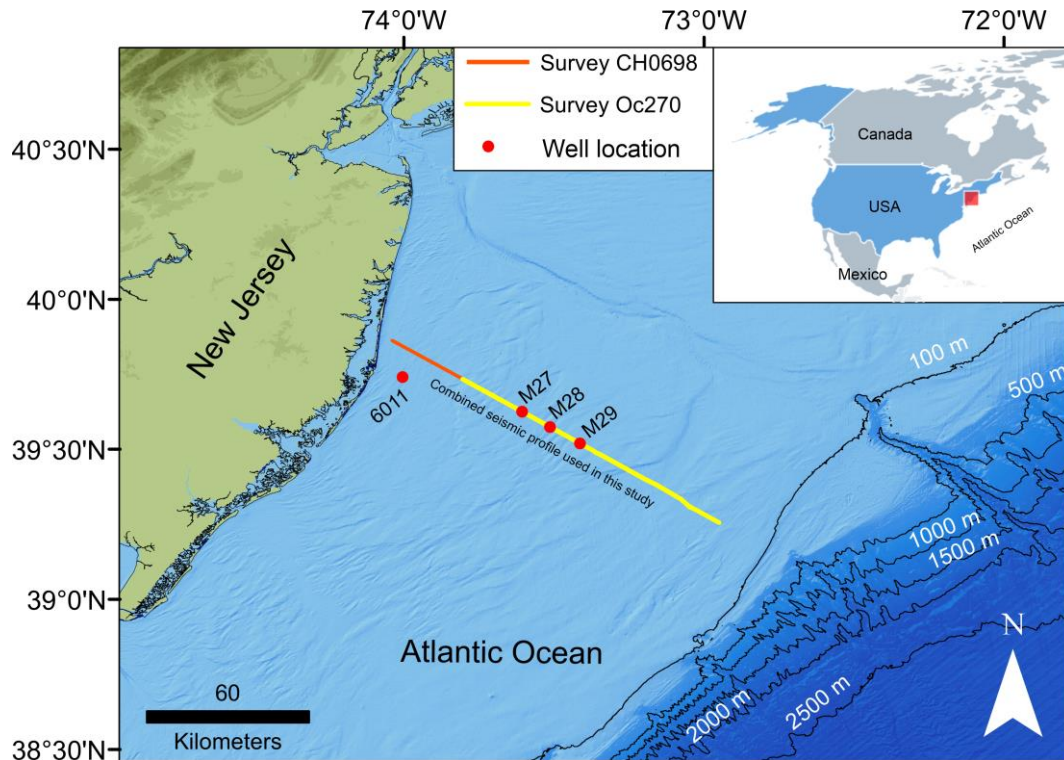
1 Introduction

Figure 1 Study location map showing composite seismic line and location of IODP Expedition 313 wells and AMCOR site 6011.

59   The existence of large reserves of fresh to brackish water in continental shelf sediments has been

60   identified as a global phenomenon (Post et al. 2013). Several studies have investigated these

61   dynamic systems in a number of settings (Groen et al. 2000; Johnston 1983; Lofi et al. 2013;

62   Micallef et al. 2020b), leading to an increased understanding of the key factors that influence the

63   emplacement and survival of offshore fresh groundwater (OFG). A study by Meisler et al. (1984)

64   identified eustatic sea-level changes as a key driver of freshwater emplacement in the New Jersey

65   shelf. Periods of relative sea-level lowstand results in increased hydraulic gradients, driving more

66   freshwater offshore. The sub-aerial exposure of shelf sediments allows for surface recharge by

67   meteoric water. Kooi et al. (2000) performed a numerical study on theoretical shelf models that

68   examined the variety of ways in which emplaced freshwater can be preserved in shelf sediments.

69   The results showed preservation to be a function of the rate of marine transgression as well as the

70   aquifer geometries in the substrate. Glacial – interglacial cycles are known to cause significant

71   sea-level variations and therefore, are fundamentally intertwined with the lifecycle of offshore

72   fresh groundwater. The impact of the Pleistocene glaciation has been examined in regional scale

73   numerical studies on the North American Atlantic margin (Cohen et al. 2010; Siegel et al. 2014).

74   These studies found that the presence of ice-sheet cover contributed significantly to offshore fresh

75   groundwater volumes. It led to increased recharge by subglacial meltwater, and enhanced offshore

76   hydraulic heads due to glacial loading.

77   The New Jersey shelf sits on the US mid-Atlantic margin, and is considered a classic passive

78   margin setting, with no significant tectonic controls on the sediments. The sedimentary record

79   shows that by the early Oligocene a major shift had occurred from a carbonate ramp deposition to

80   predominantly siliclastic sedimentation (Miller and Snyder 1997). These sediments have been

81   explored by several scientific drilling campaigns. The Atlantic Margin Coring Project (AMCOR)

82   was conducted by the U.S. Geological Survey in 1976. Hathaway et al. (1979) reported that pore

83   fluid studies revealed that much of the Atlantic continental shelf contains fresh – brackish

84   groundwater. Subsequent campaigns include the Ocean Drilling Program legs 150, 150X, 174 and

85   174X (Austin et al. 1998; Miller et al. 1994); and most recently the International Ocean Discovery

86   Program (IODP) Expedition 313 (Mountain et al. 2010). These later studies were designed to

87   investigate the link between Cenozoic sea-level change and the sedimentary record at the New

88   Jersey shelf. However, pore fluid analysis of core samples by Mountain et al. (2010) revealed

89   multiple layers of fresh – brackish groundwater in the mid-shelf region. The freshwater reservoirs

90   occur primarily in late Oligocene – Miocene sediments, with low-salinity intervals encountered at

91   depths ranging from just below the seafloor down to 500 m.

92   Since the initial discovery of extensive offshore freshened groundwater reserves during the

93   AMCOR drilling project (Hathaway et al. 1979), there have been several studies aimed at

94   understanding the hydrogeological evolution of these reservoirs. It was first assumed that the

95   freshwater body was a homogeneous, flat-lying plume, which extended oceanward becoming

96   gradually thinner and more saline. The lens was thought to be fed by submarine groundwater

97   discharge derived from the terrestrial domain. Meisler et al. (1984) conducted a series of

98   simulations on a simple, layered geological model of New Jersey shelf. The study investigated the

99   impact of sea-level, hydraulic conductivity and various permeability anisotropy ratios on the

100   position of a sharp freshwater – seawater interface. Meisler et al. (1984) concluded that the position

101   of the interface was not in equilibrium with present-day sea-level. The authors speculated that

102   freshwater could have been emplaced as early as the Miocene period. Pope and Gordon (1999)

103   investigated the position of the interface on the New Jersey shelf in numerical simulations,

104   implementing sea level variations over a period of 84 000 years. The authors concluded that due

105   to enhanced recharge and discharge of freshwater driven by a fall in sea-level, the oceanward

106   migration of the interface occurs more rapidly relative to the slow-moving rebound when sea-level

107   rises.

108   A later study analyzing oxygen isotope data by Malone et al. (2002) found that the offshore low-

109   salinity plume was not homogenous, as previously assumed. Oxygen isotope analysis of samples

110   collected in Ocean Drilling Project Leg 174a (Austin et al. 1998) revealed the internal structure of

111   the freshwater distribution in the upper 400 m of the sediment column. The variation was then

112   assumed to be related to high-porosity sand-rich intervals. Pore fluid analysis performed as part of

113   IODP Expedition 313 (sites M27, M28 and M29) revealed a multi-layered reservoir system, with

114   sharp boundaries between fresh and overlying salt water intervals (Mountain et al. 2010). Detailed

115   core analysis by Lofi et al. (2013) revealed that freshwater occurred preferentially in low-

116   permeability intervals, contrary to earlier assumptions. However, this correlation was not

117   ubiquitous. Lofi et al. (2013) presented a new hydrogeological conceptual model of the New Jersey

118   shelf that consisted of multi-layered freshwater reservoirs of varying thickness. Lofi et al. (2013)

119   also suggested that there may be multiple mechanisms of freshwater emplacement responsible for

120 present day observations. The absolute ages of pore fluid samples from IODP Expedition 313 have

121 not been determined, so the time since these samples have been buried is uncertain. A study by

122 van Geldern et al. (2013) used stable isotope geochemical analysis to argue for a modern meteoric

123 origin of the freshwater. However, the possibility of paleo-groundwater recharge in a period with

124 isotope levels similar to present-day could not be ruled out. Regional numerical studies by Cohen

125 et al. (2010) and Person et al. (2003) identify meteoric recharge during Pleistocene sea-level

126 lowstand as the key source of the freshwater. A resistivity model presented by Gustafson et al.

127 (2019) shows a high-resistivity anomaly, attributed to low salinity pore fluid, which extends

128 landward of the IODP Expedition 313 sites. The authors conclude that the anomaly, obtained by

129 jointly inverting surface-towed controlled source electromagnetic and sea-floor magnetotelluric

130 data, is consistent with land-derived recharge of the offshore freshwater reservoirs.

131 Research on the origins of the freshwater on the New Jersey shelf has therefore converged around

132 two hypotheses: (1) Fresh groundwater was emplaced during Pleistocene glacial periods, where

133 large parts of the shelf were subaerially exposed. Sea-level lowstand resulted in an increase in the

134 hydraulic head gradient, driving vigorous groundwater flow towards the open sea (Cohen et al.

135 2010; Hathaway et al. 1979; Person et al. 2003), (2) Offshore fresh groundwater reservoirs are

136 hydraulically connected with onshore aquifers, implying modern recharge by seaward-flowing

137 meteoric groundwater (Gustafson et al. 2019; van Geldern et al. 2013). To date, no study has been

138 conducted on New Jersey samples to determine absolute ages of the freshwater. Previous regional

139 studies did not aim to capture the geological heterogeneity and therefore could not conclusively

140 explain the observed layered distribution. Advances in computing capability have enabled more

141 rigorous testing of larger and increasingly complex hydrogeological models on the Atlantic margin

142 (Cohen et al. 2010; Siegel et al. 2014; Thomas et al. 2019). This has expanded the understanding

143 of mechanisms driving freshwater emplacement and subsequent survival.

144 The primary focus of this study is to use a geologically heterogeneous shelf model to test the

145 hypothesis that fresh groundwater was emplaced in New Jersey shelf sediments during the period

146 of extended sea-level lowstand associated with the Last Glacial Maximum (LGM). We conducted

147 coupled variable-density flow and heat transport simulations on the 2D shelf transect shown in

148 Figure 1. The shelf model was generated using a workflow originally presented in Thomas et al.

149 (2019). We used a stochastic modelling approach known as Sequential Indicator Simulation (SIS)

150   to determine a facies distribution, constrained by 2D depth migrated seismic and well data.

151   Porosity and permeability values are assigned to the model domain based on the facies. This

152   approach produces a geologically representative model that captures key characteristics of the

153   sediment heterogeneity and therefore accounts for its influence on the observed salinity

154   distribution. We use a process-based criterion to assess the distribution of flow connectivity in a

155   suite of 100 model realizations. We then selected the two models representing the high- and low

156   onshore-offshore connectivity cases.

157   We simulated paleo-hydrogeological conditions on the New Jersey transect during the period from

158   the LGM to present day. We consider the past 70 000 years of the hydrogeological evolution of

159   the New Jersey shelf. Firstly, simulations were performed to investigate the sensitivity of the

160   model to key factors that influence offshore freshened groundwater on the continental shelf: (1)

161   topographically driven flow (base case), (2) cemented intervals, (3) enhanced terrestrial discharge

162   and (4) permeability anisotropy. In order to model a meteoric recharge scenario, we consider the

163   specific period of the Pleistocene when the entire surface of the modelled transect was sub-aerially

164   exposed. We determined this recharge phase to be from 70 000 to 12 000 years before present

165   (BP), based on the seafloor bathymetry (Ryan et al. 2009) and sea-level data (Imbrie et al. 1984).

166   The influence of the four factors on the dynamics and distribution of fresh groundwater

167   emplacement on the New Jersey shelf was quantified by comparing the relative volumes of

168   emplaced freshwater at the end of the recharge phase, and at present day. Finally, we simulated

169   the lowstand period considering combinations of the aformentiond driving factors, as plausible

170   reconstructions of hydrogeological scenarios over the past 70 000 years. These simulations allow

171   us to draw conclusions about the evolution of offshore freshened groundwater reservoirs observed

172   in IODP Expedition 313.

173   We conducted this analysis on a detailed hydrogeological model in order to account for the role of

174   geological heterogeneity in the complex distribution presently observed. These simulations aim to

175   deduce whether meteoric recharge of freshwater on the New Jersey shelf during the last glacial

176   maximum could sufficiently explain present-day observations given a plausible reconstruction of

177   paleo-conditions.

2   Methodology

2.1   Seismic interpretation to hydrogeological model

178   Modelling paleo-groundwater flow on the New Jersey shelf poses the challenge of characterizing
181   the distribution of petrophysical properties in a domain with limited well control. In this study, we
182   generate a facies distribution model utilizing the workflow originally presented in detail by
183   Thomas et al. (2019). The approach combines seismic interpretation with well log analysis to
184   constrain a sequential indicator simulation algorithm. The seismic interpretation presented in
185   Thomas et al. (2019) was extended to include the most landward extensions of the sequences that
186   have been imaged by seismic data. Depth migrated 2D seismic lines are used to constrain the
187   sequence stratigraphic boundaries (Riedel et al. 2018). The profiles include CH068-19 (R/V Cape
188   Hatteras expedition 0698) and OC 270 lines 529, 129-429 and 29 (R/V Oceanus expedition
189   OC270). The nomenclature for the interpreted Miocene sequences were defined after Miller et al.
190   (2013). The extended interpretation is shown in Figure 2.

191   The model domain is centered on adjacent 2D seismic lines which extend 161 km from the coast
192   to close to the shelf edge. The interpretation shown in Figure 2 consists of 25 horizons, from the
193   ocean floor to the lowermost sequence boundary o1, identified as the Eocene-Oligocene boundary
194   (Miller et al. 2013). This basal sequence is the deepest horizon for which a coherent seismic event
195   could be identified. Below this surface, homogeneous model properties were assigned. The 2D
196   model domain has dimensions of 161 km x 2 km and is discretized on a finite difference grid. Cell
197   dimensions are constant throughout the model domain at 100 m in the horizontal and 10 m in the
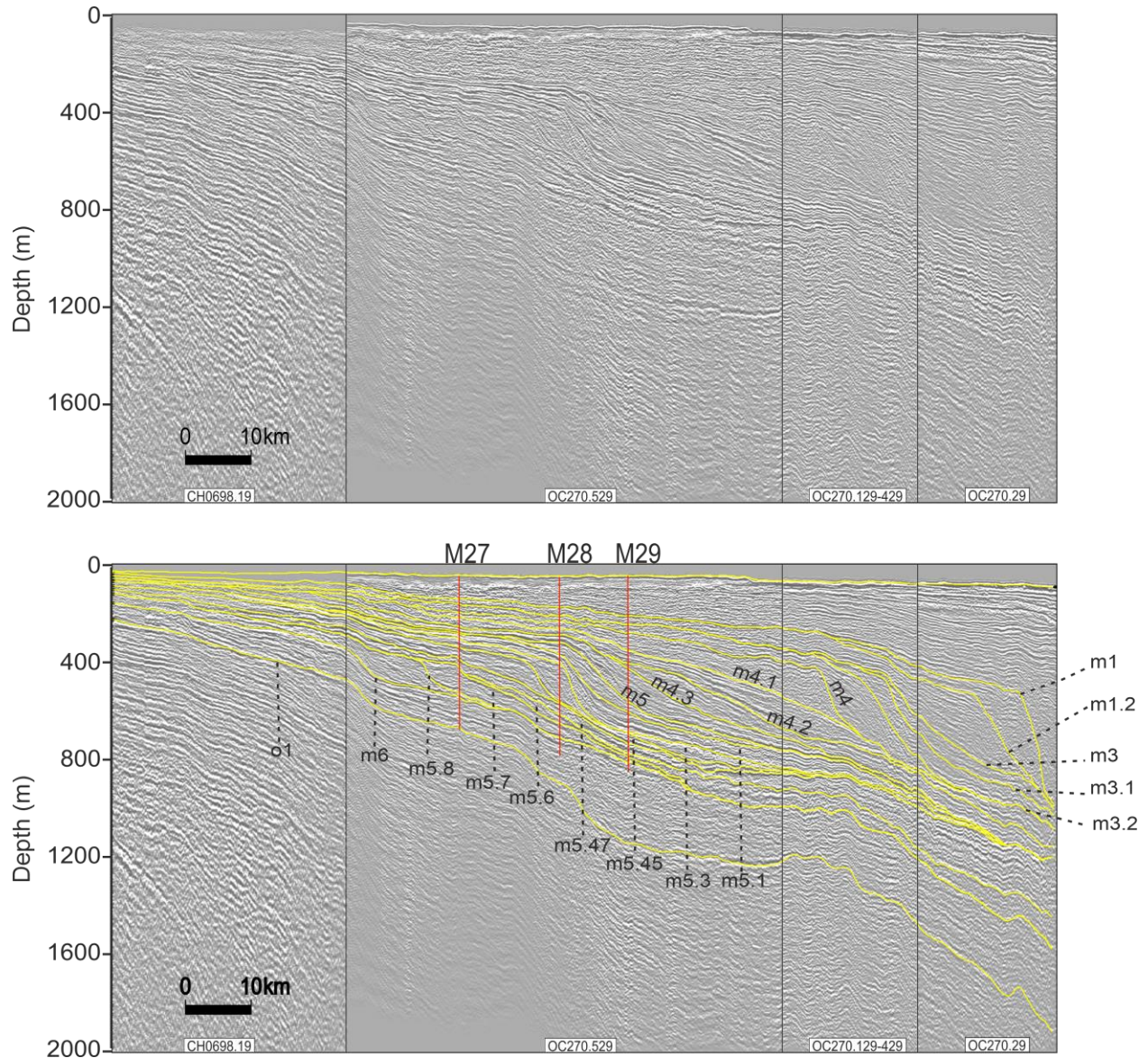198   vertical. The entire model comprises 322 000 cells.

The stratigraphic framework, shown in Figure 2 was characterized with a facies distribution using Sequential Indicator Simulations (SIS). This stochastic approach is a variogram-based simulation of categorical variables, which can be constrained by well data as well as quantified geological trends (Deutsch and Pyrcz 2014). In our implementation of the SIS algorithm, stochastic realizations are constrained by estimated vertical and horizontal correlation lengths, seismic reflector orientation, as well as vertical and horizontal probability trends derived from interpreted well log data.

209   Well data of IODP expedition 313 (Mountain et al. 2010), and AMCOR well 6011 (Hathaway et

210   al. 1979) were used to categorize the sediments into three facies types based on density logs.

211   Mountain et al. (2010) reported that density measurements corresponded to lithological changes

212   observed on core data. Therefore, we defined the following categories: sand ($\rho > 2\,050$ kg m^{-3}),

213   silt (1820 kg m$^{-3} \leq \rho \leq 2\,050$ kg m^{-3}) and shale ($\rho < 1\,820$ kg m^{-3}). The categorized well

214   logs are shown in Figure 3. It must be noted that well 6011 is a projected well, which is

215   approximately 10 km offset from the model transect. Despite this lateral offset, we assume the

216   lithological information derived from the well can be considered representative for the sediment

217   column in the proximal part of the shelf. Including this well data in the stochastic modelling

218   process introduces an additional control point and reduces the uncertainty in the proximal part of

219   the shelf.

220

221

222   *Figure 3 Interpretation and categorization of lithologies from bulk density data at well sites 6011, M27, M28, and M29. Mountain*
223   *et al. (2010) reported that density variations in IODP Expedition 313 wells broadly correspond to lithology.*

224   The categorized well log data were used to derive 1D facies probability functions. The horizontal

225   facies probability function was defined by linear interpolation of control points, each

226   corresponding to a single well. We calculated the probability of occurrence of each category over

227   the entire well. This probability was defined for each facies category as $P_i = n_i/n_T$, where n is the

228   number of samples of the category denoted with subscript i, and n_T is the total number of samples.

229   In the absence of well data, a distal control point was assigned at the boundary of the model

230   domain. At this location, we assume $P_{shale} = 0.75$, $P_{sand} = 0.1$ and $P_{silt} = 0.15$. This method of using

231   the proportion of each facies is a standard approach to incorporate geological trends into stochastic

232   models (Deutsch and Pyrcz 2014). In deltaic environments like the New Jersey shelf, it is typical

233   that fine-grained sediments are transported further basinward, resulting in a general offshore fining

234   trend in the lithology (i.e., increasing probability of shale). The trends obtained from four wells is

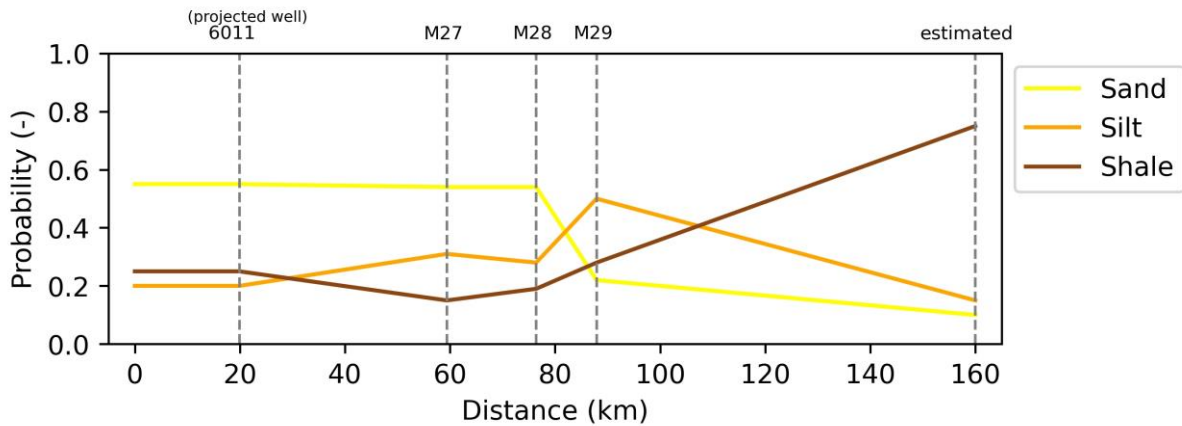235   shown in Figure 4.

236

237   *Figure 4 Horizontal facies probability functions calculated by linear interpolation between control points.*

238   The horizontal trends were assigned globally for the model domain. Vertical trends were

239   incorporated by calculating vertical proportionality curves for each sequence individually using

240   well data analysis tools in Petrel. These trends jointly contrain the sequential indicator simulation

241   algorithm and incorporate realistic geological features into the suite of models produced. The

242   model domain is thereby populated with the three facies types, to which petrophysical properties

243   were later assigned for numerical simulation. Cemented intervals identified by core analysis

244   presented in Lofi et al. (2013) were included deterministically in the model framework. These

245   high-density intervals lead to high acoustic impedance at the cemented regions of the sequence

246   boundaries (Miller et al. 2013a). We approximate the lateral extent of these cemented layers based

247   on the interpretation presented in Lofi et al. (2013) as well as the amplitude of the reflectors.

248   The final input to the stochastic model are the variogram parameters. In the absence of sufficient

249   well data for variogram modelling, we estimate the variogram parameters based on the

250   depositional model. The New Jersey clinothem system is penetrated at the topset, rollover and

251   bottomset positions by IODP wells M27, M28 and M29 respectively (Mountain 2010). This system

252   of prograding clinoforms is at least 22 km across and interpretation of sequences across the wells

253   has been established based on seismic data (Miller et al. 2013b), as well as biostratigraphic

254   interpretation (Browning et al. 2013). Generally speaking, the dimensions of shoreface-shelf

255   deposits for wave-dominated delta system have a wide range from a few kilometres up to 30 km

256   (Hampson 2010; Reynolds 1999). The continuity of facies along the dip direction is determined

257   by the shoreline progradation distance of the delta during the time of deposition. Using this model,

258   we assigned a correlation length of 15 km for the variogram model as an average repsresentative

259   value for the entire system. In addition to the correlation length, we defined a dip angle of

260   maximum correlation for each sequence. This was determined from the average dip of the seismic

261   reflectors in the sequence. These values ranged between 0.25° and 1.2°.

262   The matrix properties were assigned to the model domain based on the interpreted lithology.

263   Porosity compaction trends were derived from core-sampled porosity data measured by Mountain

264   et al. (2010). The data of each facies group was fitted to an empirical exponential equation first

265   described by Athy (1930):

266    $$\theta = \theta_0 e^{-az} \tag{1}$$

267   where θ is the porosity at depth z (m), θ_0 is the initial porosity and a is the correlation coefficient.

268   Two trends were derived based on the log data, a sand compaction trend and a silt/shale

269   compaction trend. The three categories sand, silt and shale correspond to high, medium and low

270   permeability, respectively. Matrix parameters are summarized in Table 1.

271

272

273   *Table 1 Summary of matrix properties used in all simulations*

Parameter	Value	Unit	Reference
Permeability	[†]9.4×10^{-12} [*]7.4×10^{-14} [††]9.0×10^{-16}	m^2	(Lofi et al. 2013; Thomas et al. 2019)
Porosity	[†]$44.7\, e^{-2.46\times10^{-4}\, z}$ $57.5\, e^{-5.93\times10^{-4}z}$	-	(Mountain et al. 2010; Thomas et al. 2019)
Thermal conductivity	[†]2.9 [*]2.3 [††]1.7	W m⁻¹ K⁻¹	(Mountain et al. 2010)
Volumetric Heat capacity	[†]2.4×10^6 1.9×10^6	J K⁻¹ m⁻³	

274   † - sand, * - silt, †† - shale

275

2.2   Stochastic simulation and model selection

277   The SIS algorithm generates multiple stochastic realizations of equally probable scenarios, which

278   honour the input data. However, SIS does not consider the connectivity of the model domain. The

279   lateral flow connectivity is an important consideration in assessing the hydrogeologic evolution of

280   the freshened groundwater reservoirs on the New Jersey shelf, and the potential role of modern

281   day recharge.   Connectivity of stochastic models are often assessed by calibration of facies

282   distribution with field pumping data (Zhou et al. 2014). In the absence of such data for our study

283   domain, we conducted a simple Monte Carlo sampling from a suite of 100 model realizations to

284   select models to use for numerical simulations (Deutsch and Pyrcz 2014).

285   The steady-state solution of the hydraulic head was used to derive a simple metric that is related

286   to an important aspect of the system, the onshore – offshore connectivity of the realization. This

287   process-based model selection approach is a standard practice in geostatistical reservoir modelling

288   (Deutsch and Pyrcz 2014). The models were initiated with hydrostatic conditions, and fixed head

289   boundary conditions at the lateral boundaries such that a 25 m hydraulic head difference was

290   maintained between the landward and oceanward boundaries. That value was chosen based on

291   results presented in Cohen et al. (2010), which estimated that conditions during the LGM resulted

292   in head values along the New Jersey that may have been 25 m higher than present-day. After

293   calculating the steady-state solution, the horizontal distance between the land boundary and the

294   average position of the contour representing a 10 m increase in head within the model domain was

295   measured. A longer distance would correspond lower hydraulic gradient, an indication of higher

296   flow connectivity between two points (Freeze and Cherry 1979).   Based on the probability

297   distribution of this distance, two model realizations were chosen for numerical simulations

298   representing high- and low onshore-offshore connectivity scenarios. Numerical simulations were

299   performed on both model scenarios.

300

301   Summary statistics calculated on the lateral distance to the 10 m contour line show an average

302   distance of 48.4 km with a standard deviation of 27 km. The probability density function (PDF)

303   was estimated using a gaussian kernel density estimation (Hastie et al. 2009). This is a non-

304   parametric method that estimates the PDF of a continuous random variable. The PDF shown in

305   Figure 5, has a bimodal distribution, which points to low-to-intermediate connectivity as the more

306   likely scenario given the currently available data. A less likely scenario is high connectivity.
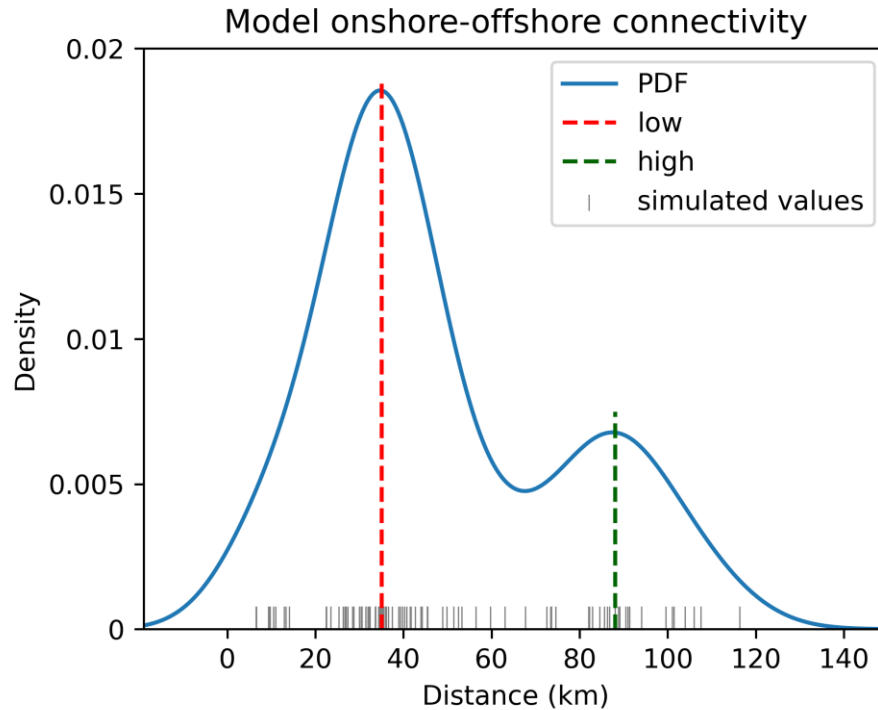
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309   *Figure 5 Probability density function of model connectivity metric showing a bimodal distribution for a suite of 100 stochastic*
310   *model realizations. The positions of the low and high onshore-offshore connectivity modes are indicated by red and green dashed*
311   *lines, respectively. The realizations with values closest to these two modes were selected for numerical simulation.*

312   Based on these summary statistics, we conducted numerical studies using two realizations,

313   representing low and high connected mode scenarios. The models with the connectivity values

314   closest to the two modes were selected. The high and low connectivity scenarios were represented

315   by realizations 97 and 51, respectively. These realizations are shown side by side in Figure 6. The

316   steady-state hydraulic head contours are overlaid on the model domain.
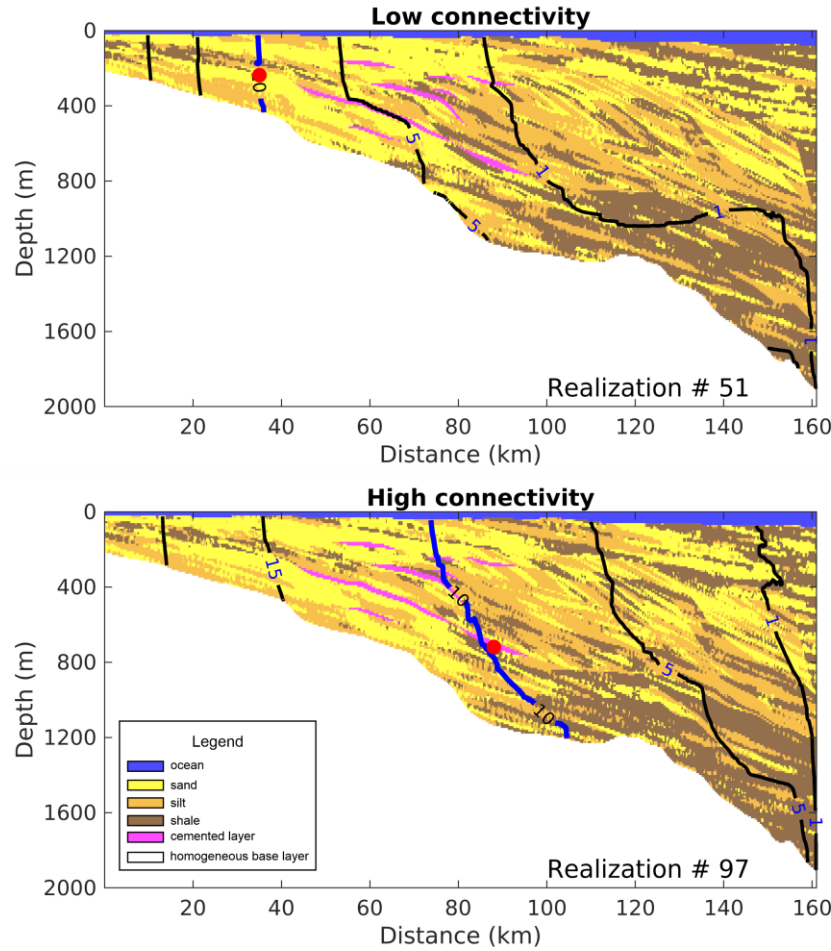
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Figure 6 (a) Low onshore-offshore connectivity model (b) High onshore-offshore connectivity model realizations. Both models show the position of the 10 m hydraulic head contour in bold blue. The models were ranked based on the horizontal distance between the landward boundary and the average position of the contour indicated by the red dot. The corresponding porosity compaction models are included in the Supporting Information of this manuscript (Fig. S1)

2.3 Modelling the offshore freshened groundwater system

Numerical simulations were performed using a finite difference numerical modelling algorithm called SHEMAT-Suite (Clauser 2003; Keller et al. 2020; Rath et al. 2006). We simulate variable-density groundwater flow coupled with heat transport, taking into consideration the key drivers of fresh/saline groundwater flow on this regional scale model. Clauser (2003) provides a detailed description of the partial differential equations implemented in SHEMAT-Suite for groundwater flow, heat and solute transport. The parameters assigned to the flow model are the same as in Thomas et al. (2019). These are summarized in Table 2.

332

333

Table 2 Summary of model parameters used in all simulations

Parameter		Value	Unit	Reference
Fluid properties	Reference Density (freshwater)	1 000	kg m^{-3}	(Freeze and Cherry 1979)
	Compressibility	4.58×10^{-10}	Pa^{-1}	
	Viscosity	1.0×10^{-3}	Pa s	
	Thermal Conductivity	0.6	W m^{-1} K^{-1}	(Ramires et al. 1995)
	Specific heat capacity	4128	J K^{-1} kg^{-1}	(Siegel et al. 2014)
Solute transport	Molecular Diffusion Coefficient	1.1×10^{-9}	m^2 s^{-1}	(Freeze and Cherry 1979)
	Molar Mass (NaCl)	58.44	g mol^{-1}	(Manahan 2011)
	Dispersivity	50	m	(Gelhar et al. 1992)

334

We simulated 70 000 years of the Pleistocene lowstand. During this period, the sealevel fell as low as 120 m relative to present-day (Imbrie et al. 1984). As a result, large areas of land were subaerially exposed on the low-angle passive margin platform of the New Jersey shelf. For the purpose of this analysis, we define two distinct phases of this period. The recharge phase from 70 000 to 12 000 years BP, and the flooding phase from 12 000 years BP to present day. That starting point was chosen as it is approximately when the entire transect of the ocean floor (Figure 2) became subaerially exposed. A set of idealized simulations were designed to investigate the sensitivity of freshwater emplacement as hydraulic conditions on the shelf responded to sea-level lowstand.

The numerical study is presented in two phases. Firstly, we assess the model sensitivity to topographic-driven flow (base case), cemented intervals, enhanced terrestrial discharge and permeability anisoptropy. Topographic-driven flow refers to the lateral hydraulic gradient induced by the seafloor topography. We consider this the base case, as the shelf exposure is the essential condition that allows meteoric recharge. The cemented intervals have been identified in core samples, and found to be correlated with the fresh – saline pore fluid boundaries reported in previous petrophysical studies (Lofi et al. 2013; Mountain et al. 2010). We simulated a hypothetical scenario in which these intervals were assigned regular matrix properties of silt (Table 1), in order to quantify their impact. Enhanced terrestrial discharge (ETD) refers to offshore-directed flow generated at the landward boundary of the model, accounting for a subterranean influx of freshwater. This was modelled by an increased hydraulic head at that boundary. The

355   assigned value was based on computed heads during the Pleistocene and Holocene along the

356   Atlantic continental shelf modelled by Cohen et al. (2010). Their simulations accounted for

357   conditions induced by ice sheet loading and sealevel fall, and estimated up to 25 m increase in

358   hydraulic head on-shore in the region near our model transect. Finally, we investigate the influence

359   of anisotropic permeability. Anisotropy is a common feature in sedimentary environments due to

360   the influence of bedding and possible compaction banding (Holcomb and Olsson 2003; Vajdova

361   et al. 2004). In this study, we define the anisotropy in terms of the ratio of horizontal permeability,

362   k_h and vertical permeability, k_z. We consider two plausible values of the anisotropic ratio, two and

363   ten. The set of simulations described above was conducted on both high and low connectivity

364   model realizations. Boundary conditions for all scenarios are summarized in the following section.

365   The scenarios were compared based on three observation criteria. Firstly, the volumetric trend of

366   fresh pore fluid in the model domain over the simulated time. Although the model is 2D, the

367   volumes were calculated based on the cell with of 100 m, and the pore volume of each cell.

368   Secondly, the present-day pore fluid concentration profiles were compared to measured data at the

369   four wells sites for each scenario. Finally, the pore fluid concentration distribution in the model

370   domain was analysed at two key times, the end of the recharge phase and at present day to consider

371   the role of geological heterogeneity.

372   In the second phase, we conduct a comprehensive set of simulations on a single representative

373   model realization, designed to reconstruct conditions over the period from 70 000 years BP to

374   present-day. For this phase, we consider only the low onshore-offshore connectivity realization

375   (Fig 6 a), as it corresponds to the highest likelihood based on the probability distribution (Fig. 5).

376   We consider the compounded effect of topographic-driven flow, enhanced terrestrial discharge

377   and permeability anisotropy. At the end of these simulations, the pore fluid concentration in the

378   model domain was compared to present-day observations in IODP Expedition 313 wells and

379   AMCOR well site 6011. This comparison, together with the distribution of freshened groundwater

380   in the model domain is analysed to draw conclusions about the dynamic nature of the OFG system.

381   The volume of freshwater in the model domain over time is considered as a metric for quantifying

382   the influence of the abovementioned factors. Ocean water has a total dissolved solid (TDS)

383   concentration of approximately 35 g L^{-1}. For the purpose of this study, the modelled solute is NaCl,

384   which has a molar mass 58.443 g mol^{-1}. This translates to, and is specified in SHEMAT-Suite as

385   a molecular concentration of 0.6 mol L^{-1}. In this study, pore fluid is defined as freshwater when it

386   has a solute concentration of less than 0.3 mol L^{-1}, i.e., approximately half the TDS concentration

387   of seawater (~17.5 g/L TDS).

2.3.1   Initial and boundary conditions

389   The coupled variable-density flow and heat transport simulations in this study require compatible

390   boundary conditions for groundwater flow, heat and solute transport. The boundary conditions

391   were designed to be consistent with laws of conservation of mass and energy within the model

392   domain. All simulations were initialized under the same conditions to facilitate comparison.

393   The initial temperature and hydraulic head distribution in the model domain were set to the steady-

394   state solution of their respective equations. For temperature, surface cells were assigned a Dirichlet

395   boundary condition of 4 °C, representing the average surface temperature during the recharge

396   phase (Johnsen et al. 1995). Basal specific heat flow was prescribed by a Neumann boundary

397   condition of 0.06 W m^{-2} (Lachenbruch and Sass 1977). The groundwater flow was constrained by

398   a Dirichlet boundary condition assigned along the surface cells and lateral boundaries. The head

399   in each surface cell was set to its elevation relative to the model datum. At the landward and

400   oceanward boundaries, the head was set to the elevation of their respective surficial cells. We

401   invoke the simplifying assumption that the hydraulic gradient mirrors the surface topography, and

402   consider only saturated flow (Freeze and Cherry 1979). Determining initial salinity distribution is

403   challenging as the position of the freshwater – seawater interface is transient and dynamic (Meisler

404   et al. 1984). We assume the domain is fully saturated with saline pore fluid (0.6 mol L^{-1} or 35 g L^{-}

405   ^{1} TDS) in all cells below sealevel, shown in Figure 7. This represents a conservative initial estimate

406   as it is likely that more freshwater recharge would have taken place as the transect was partially

407   exposed i.e., prior to our simulated period. Therefore, the model may underestimate the volume of

408   freshwater that would have been emplaced over the entire regressive – transgressive cycle. This

409   initial condition has also been implemented in a comparable regional numerical study (Siegel et

410   al. 2014). The assumption isolates the simulated period as a minimum baseline for recharge, and

411   provides a reference point from which to ascertain whether older freshwater emplacement is
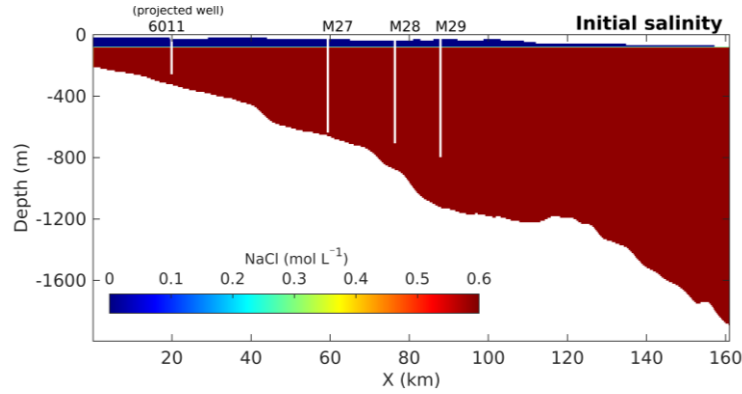
412   needed to explain the present-day observations.

413

414

415   During the recharge phase, surface temperature was fixed to the initial condition described above,

416   with the steady-state thermal gradient at the lateral boundaries. Dirichlet boundary condition of

417   zero salinity was assigned to the model surface. This represents meteoric recharge, which is known

418   to have negligible salinity (Selley and Sonnenberg 2015). The landward and oceanward lateral

419   boundaries were set to 0.0 mol L⁻¹ and 0.6 mol L⁻¹, respectively. The hydraulic head at the surface

420   and landward boundaries were set to the surface elevation. The unsaturated zone and associated

421   infiltration processes are assumed to be negligible. This assumption is validated considering the

422   large aspect ratio between the model length and the depth of the sediments under investigation

423   (Freeze and Cherry 1979).

424   At the oceanward boundary, we assigned a time-varying Robin boundary condition. This specifies

425   flow across the model boundary using the formulation as described in Jazayeri and Werner (2019):

426
$$Q = -\frac{KA}{L}(h - h_{ref}) \tag{2}$$

427   where K (m s⁻¹) is the hydraulic conductivity of the extended region, A is the cross-sectional area

428   of the boundary, $h - h_{ref}$ (m) is the head drop between the model boundary and an external

429   reference point and L (m) is the distance between the model boundary and that point. The reference

430   head, h_{ref} is the sealevel elevation at the shelf edge. The values were sampled from the relative

431   sealevel curve by Imbrie et al. (1984) at 2000 year intervals, as summarized in Figure 8. This type

432   of boundary condition is applied as our model transect does not extend all the way to the shelf

433   edge. This head dependent flux approximates the hydraulic conditions of the shelf region outside
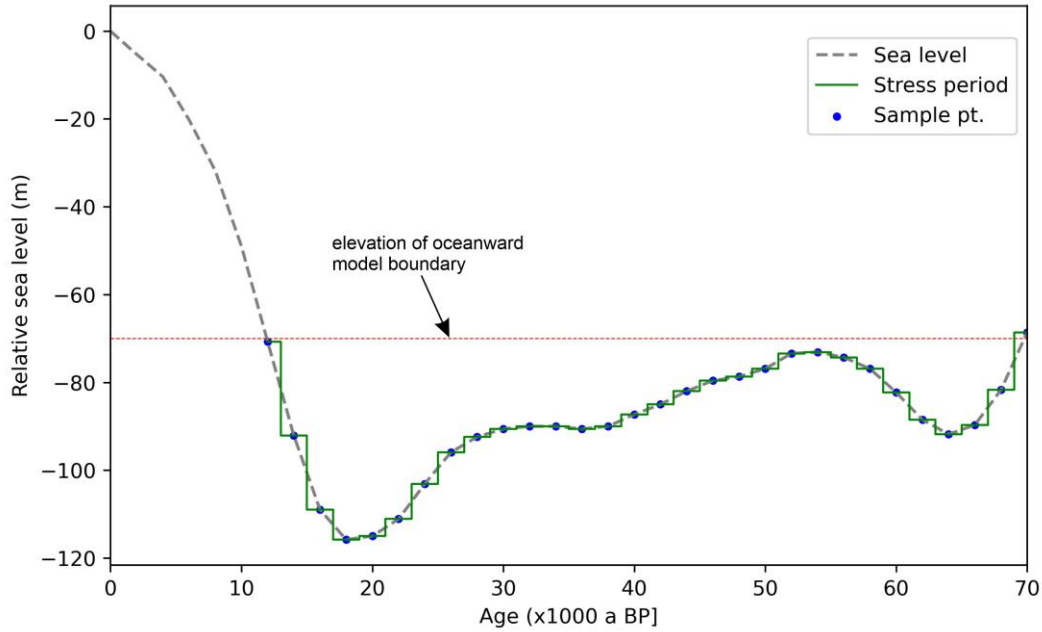
434   of the model domain.

435

Figure 8 Relative sea level curve of the past 70 000 years used to determine boundary conditions for model domain. Blue dots show the sample points (h_{ref}) and light green lines indicate 2000 year period for which the value was applied. The red dashed line represents the level of the model's oceanward boundary (h).

439   For our model domain, A = 1.92×10^5 m^2 based on the cell dimensions, and the distance from

440   the model boundary to the shelf edge L = 25 000 m. We estimated a value of K = 7.6×10^{-8} m

441   s^{-1} as the average hydraulic conductivity for the distal section of the shelf. The main model

442   boundary conditions during the recharge phase are summarized in Figure 9. The conditions were

443   applied in all cases with the exception of ETD. In that scenario, shore-parallel flow was enhanced

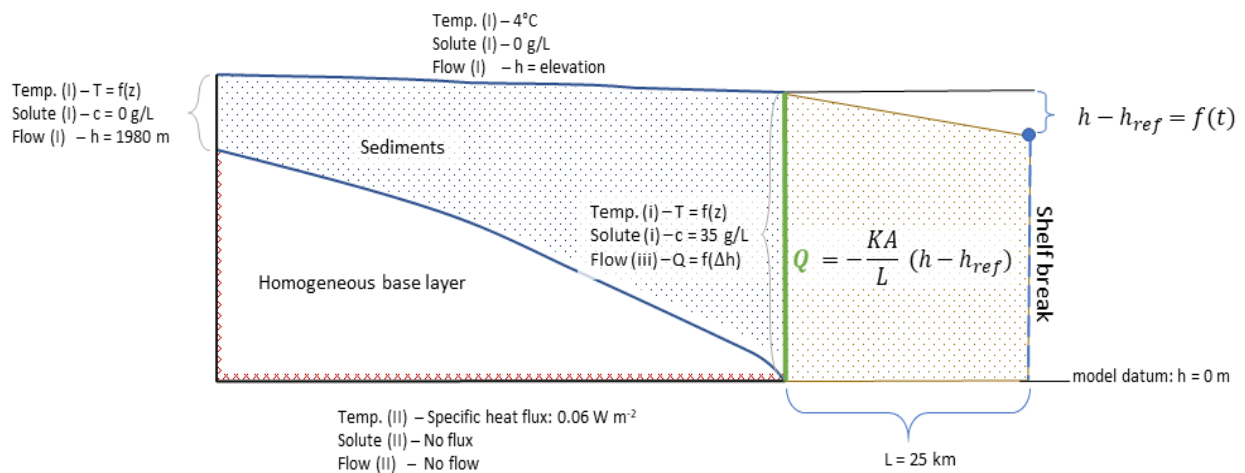444   by increasing the head at the landward boundary by 25 m.

445

447   *Figure 9 Recharge boundary condtions. (i) Dirichlet type boundary condtions, (ii) indicates Neumann type boundary conditions, and*
448   *(iii) Robin boundary condition. Red hashed line represents no flow conditions assigned to the homogeneous base layer.*

449   <u>Flooding Phase</u>

450   During the 12 000-year period of Holocen transgression, the topographic flow regime of the

451   recharge phase passes over into today's hydrostatic conditions. Each model run was initialized

452   using pore fluid concentration obtained at the end of the corresponding recharge phase. Time-

453   dependent boundary condition functions were implemented in SHEMAT-Suite to represent a

454   transgressing coastline during the simulated period. The hydraulic head at surface cells was

455   increased to sea-level elevation as the model domain is gradually flooded. The head at the

456   oceanward boundary was intiated at the surface elevation and increased over the transgressive

457   period to the present-day sea level at that point of the shelf. The head at the landward boundary

458   was set to 5 m above surface elevation. The salinity of the relevant surface nodes was increased to

459   ocean salinity according to the timing of the marine transgression. The surface temperature was

460   also increased linearly from 4 °C to the present-day average sea-surface temperature of 14 °C

461   (O.S.P.O. 2013). Temperature at the lateral boundaries was fixed to the steady-state thermal

462   gradient.

463

3   Results

3.1   Numerical simulation of freshwater emplacement

In the following sections the results of the numerical simulation are presented in detail. Firstly, we present observations of the freshwater emplacement mechanism in the context of a heterogeneous shelf model. This is followed by sensitivity analysis comparing the influence of various hydrogeologic scenarios. Finally, we present a paleo-hydrogeological reconstruction of the LGM on a representative shelf model.

3.1.1   Analysing the mechanism of freshwater emplacement

This section presents the results of topographically driven flow for both high and low onshore-offshore connectivity cases, abbreviated as HC and LC, respectively. The mechanisms by which freshwater is emplaced in the sediments are analysed in the context of the heterogeneous shelf models.

Figure 10 shows the progressive freshening of the shelf sediments in the base case in the low onshore-offshore connectivity model. The figure shows snapshots of the recharge phase taken in the periods between 68 ka BP to 64 ka BP, and 28 ka BP to 12 ka BP. These correspond to the periods of most rapid sealevel change (see Fig. 8) and the most observable changes in pore fluid concentration. It can be observed that due to topographically driven flow during the simulated sea-level lowstand, freshwater is emplaced across the entire shelf transect to varying depths. The interface between fresh and saline water is highly complex as a result of the geological heterogeneity. The depth of freshening becomes gradually more shallow in the oceanward direction. The result indicates that the offshore directed hydraulic gradient resulting from surface topography is sufficient to drive freshwater into sediments across the entire shelf transect. The most distal part beyond 120 km from the shore is relatively flat, leading to much slower rates of freshening. In general, a downward movement of the fresh – saline interface occurs in response to a sea-level lowstand. Top-down freshening by surface derived recharge appears to be the primary mechanism driving the emplacement of freshwater. In a topographically driven flow regime, the recharge is focussed into high permeability intervals (Hobbs and Ord 2015). As a result of the hydraulic gradients, recharged freshwater is driven laterally into aquifer units, while overlying

492   confining units remain saline for a longer period. Furthermore, this preferential flushing of
493   permeable intervals causes density instabilities, resulting in density-driven free convection
494   between the saline pore fluid in the confining units and the underlying freshened aquifer units.
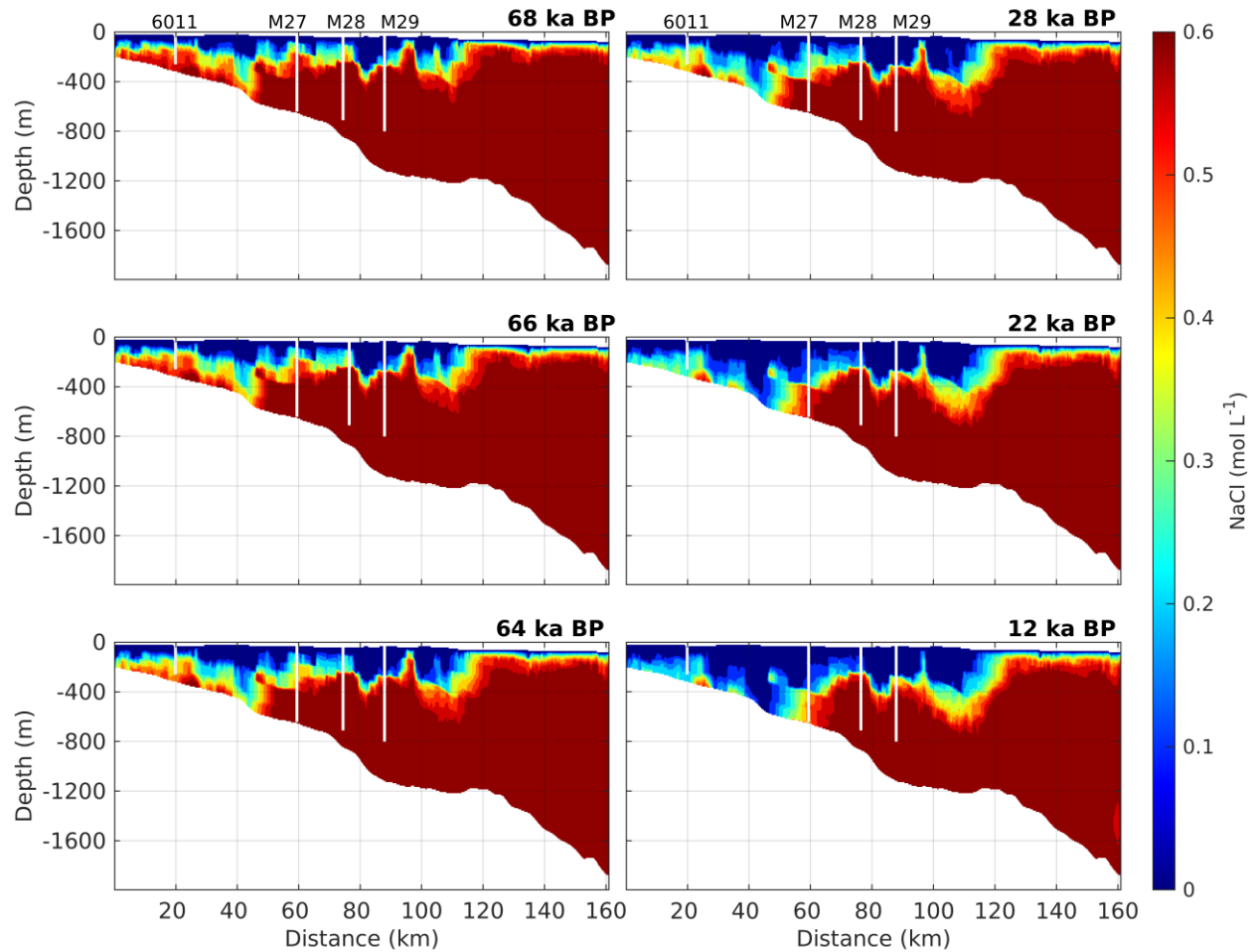

495

496   *Figure 10 Solute concentration in the model domain during the recharge phase for the base case scenario in the low onshore-*
497   *offshore connectivity model realization. Snapshots of the transient results show the complexity of freshwater recharge in the*
498   *heterogeneous subsurface. Freshening occurs by a combination of advective flow in aquifer units and density-driven free convection*
499   *in confining units. Freshening appears to occur primarily from the surface recharge.*

500   The recharge phase displays similar dynamics in the high onshore-offshore connectivity model,
501   shown in Figure 11. These results indicate that the recharge of freshwater during lowstand is
502   primarily a function of topography and geological heterogeneity. Marginal changes in the pattern
503   of freshening can be seen in the proximal part of the shelf as a result of the higher onshore-offshore
504   connectivity. However, the general position and shape of the fresh – saline water interface closely
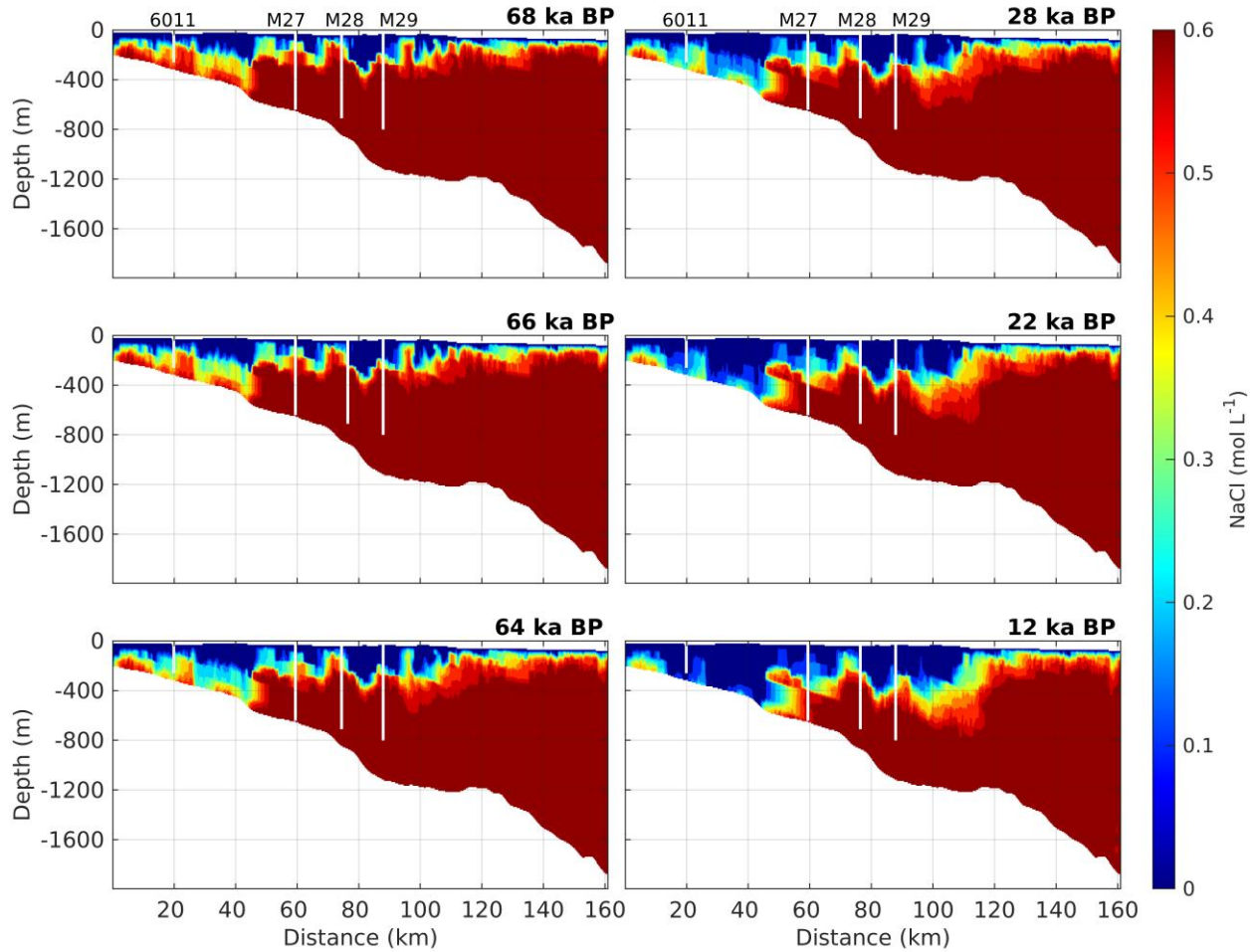505   match the LC model.

506
507 *Figure 11 Solute concentration in the model domain during the recharge phase for the base case scenario in the high onshore-*
508 *offshore connectivity model realization. The distribution at the end of the recharge phase (12 ka BP) shows more evidence of*
509 *channelized flow of freshwater when compared to the low connectivity case. Top-down freshening by surface recharge is*
510 *restricted by laterally continuous aquitards present in this model.*

511 The pore fluid concentration at the end of the recharge phase is shown for both models in Figure

512 12. It can be observed that freshwater is driven deeper in proximal regions of the shelf, where the

513 sediment column is primarily sandy. Toward the distal shelf regions, there is a decreasing trend in

514 grain size, which correlates with shallower penetration of freshwater. The shape of the fresh –

515 saline interface shows considerable lateral variability corresponding to the stratigraphic

516 terminations of sandy units. This highlights the importance of capturing the sequence stratigraphic

517 architecture. A local topographic high around 100 km also corresponds to relatively deeper

518 penetration of freshwater recharge. As surface elevation increases inland, freshwater is driven

519 deeper into the sediment column. Freshwater was driven as deep as 500 m in the region of IODP

520 well M27, both high- and low-permeability intervals are completely flushed with freshwater. The

521 region around M28 shows freshwater recharge occurring down to about 300 m depth. Deeper

522   freshening appears to be impeded by the presence of cemented and low-permeability intervals
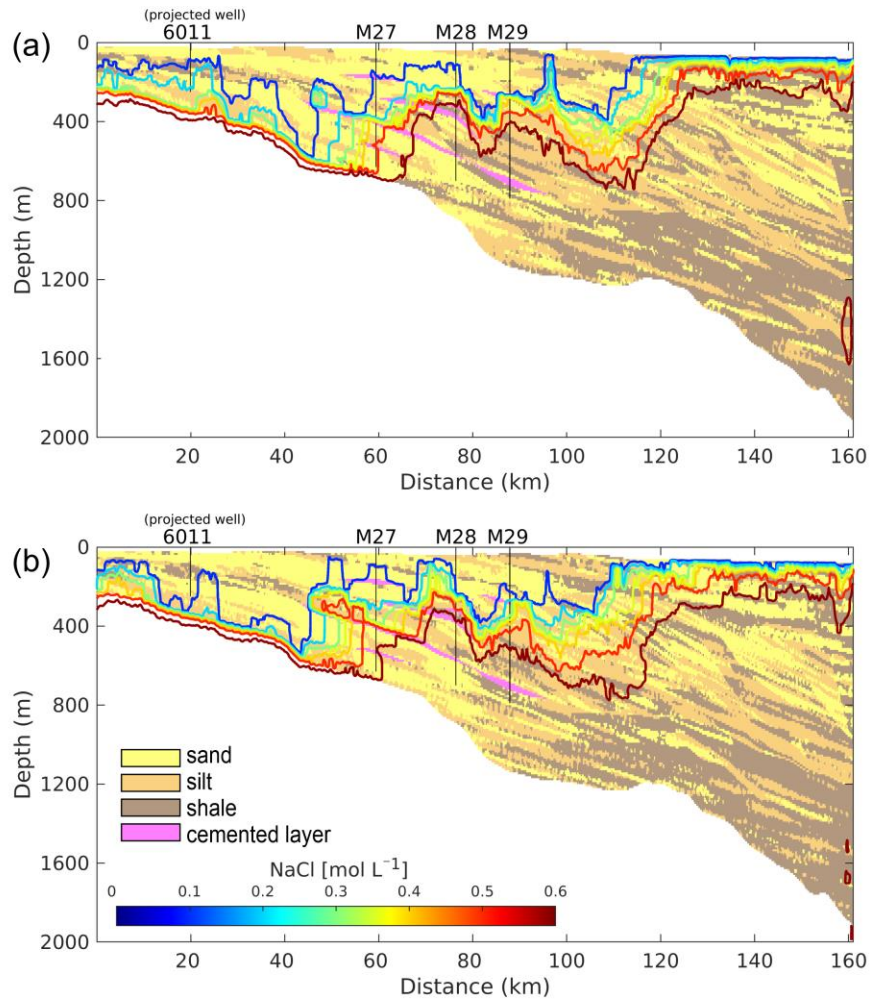523   below 300 m.

524

525

Figure 12 (a) Low onshore-offshore connectivity, (b) High onshore-offshore connectivity. Pore fluid concentration contours in model domain at the end of the recharge period (i.e. 12 000 years BP) overlaid on the facies model highlighting the correlation between geological heterogeneity and the distribution of freshwater recharge.

529   The presence of low-permeability sediments near the surface is a feature of the subsurface
530   heterogeneity that strongly influences freshwater recharge. The HC model, shown in Figure 12 b,
531   features some near-surface shale intervals in the mid-shelf region between 50 km – 80 km which
532   are absent in the LC model. While these aquitards create conduits that increase the lateral flow
533   connectivity in the model domain, they also have the effect of reducing the depth of penetration of
534   surface derived recharge. This influences the extent to which the underlying sediments are
535   freshened in the HC model relative to the LC model. The effect can also be observed in the
536   proximal region of the models where more freshening occurs in the HC model due to

537 discontinuities in the confining layers. The near-surface distribution of low-permeability

538 sediments influences the emplaced freshwater volumes such that the LC model facilitates more

539 recharge relative to the HC model. The relative volumetric trends are presented in the following

540 section.

541 **3.1.2   Sensitivity analysis**

542

543 Freshwater volumetric trends

544

545 In this section we present the simulation results for all scenarios in the high onshore-offshore

546 connectivity (HC), and the low onshore-offshore connectivity (LC) models. We compared the two

547 model realizations based on three sets of observation: (1) freshwater volume trends over the

548 simulated period, (2) fluid concentration at the end of the recharge phase and present-day, and (3)

549 fit between observed and measured pore fluid concentration at well locations.

550

551 Figure 13 shows the freshwater volume trend for the 70 000 year simulated period in both model

552 realizations. There are two periods of rapid increase in freshwater emplacement that coincide with

553 rapid sea-level fall. These occur from 70 000 years BP to 60 000 years BP and about 28 000 years

554 BP to 18 000 years BP. The time of relatively slower regression between these two periods is

555 characterized by a gradual linear increase in the freshwater volume. This pattern is replicated in

556 both the HC and LC model realizations. A key observation is that all the curves show a similar

557 trend to the base case. This suggests that the dominant mechanisms during the lowstand are

558 meteoric recharge and topographically driven flow.

559

560 Removing the cemented intervals resulted in a moderate increase in emplaced freshwater relative

561 to the base case (10 % - 14 %). The volume that survived until present day was only marginally

562 smaller than the base case (blue curves in Fig. 13). This suggests that while cemented intervals

563 strongly influence the geometry of surviving freshwater reservoirs, they are not significantly more

564 influential than low-permeability shales on the overall reservoir volumes.

565

566 The ETD scenario resulted in a 2.1 % increase in the freshwater volume for the HC model and <

567 1 % in the LC model realization. This result is consistent with the difference in onshore-offshore

568 connectivity between both models. In our model domain, the sediment column on the landward

569   boundary is 300 m thick, therefore this may underestimate the amount of discharge that enters into

570   the offshore environment e.g., through deeper connected pathways.

571

572   The anisotropic permeability scenarios had the most significant influence on the emplaced

573   freshwater volume. In the case of a horizontal to vertical ratio of two, the freshwater volume was

574   reduced by 20 % in the LC model and 12.3 % in the HC model, relative to the base case. In both

575   models the present-day freshwater volume is approximately equal to the base case. The anisotropy

576   reduces the emplaced volume, but also acts to preserve more of the emplaced freshwater during

577   subsequent regression. An increase of the anisotropy ratio to ten, led to a further decrease in the

578   emplaced volumes and a significant flattening of the volumetric trend. We observed a very

579   dampened response to the periods of rapid sea-level fall. In that case, the freshwater volume was

580   reduced by 57.7 % in the LC model and 54.6 % in the HC model relative to the respective base

581   cases. In the presence of strong anisotropy, effectively all of the recharged freshwater is salinified

582   during the subsequent flooding phase, as shown by the magenta colored curves in Figure 13. These

583   observations highlight the significance of downward infiltration of meteoric recharge through the

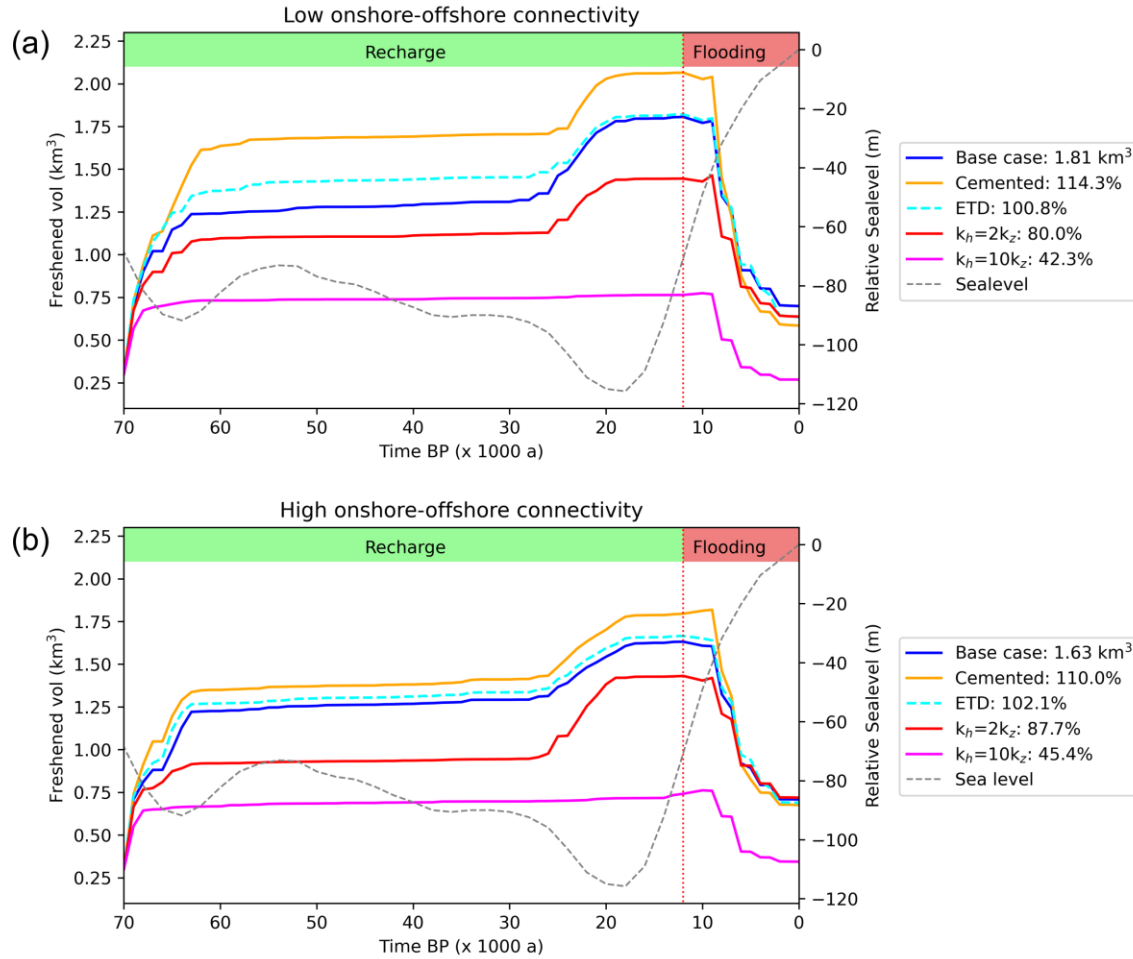584   sediment column from the model surface.

585
586 *Figure 13 The volume of freshwater over the simulated period is plotted for all scenarios in (a) LC model and (b) HC model. The*
587 *legend shows the volume of freshwater emplaced during the recharge phase for the base case, and the relative percentages at the*
588 *end of the recharge phase are shown for all other scenarios. The dashed grey line shows the sea-level curve after Imbrie et al.*
589 *(1984) plotted on the secondary y-axis (right).*

590 Model concentration distribution
591

592 The distribution of pore fluid concentration in the model domain is shown at two key times i.e.,

593 the end of the recharge phase at 12 000 years BP, and present-day. We present results of the low

594 onshore-offshore connectivity model in Figure 14, where each panel displays a different simulated

595 scenario. In the recharge phase, we can observe that more freshening occurs in the region of M27

596 in the absence of cemented intervals (Figure 14 b). The ETD scenario shows only minor changes in

597 the distribution within a range of 20 km from the landward boundary (Figure 14 c). Figure 14 (d) and

598 (e) show the low and high anisotropy ratio cases, respectively. These result in an upward shift and

599 general flattening of the fresh-to-saline interface. In the case of high anisotropy, freshening only

600 occurs to ~ 300 m. With the exception of the high permeability scenario, the present day

601   distributions consistently reproduce a seaward-dipping zone of fresh water extending from the

602   landward boundary to ~ 40 km offshore. Downward fingering of saline pore fluid can be observed

603   separating the freshwater interval at site M27. In the case of low anisoptropy, this separation is

604   characterized by a relatively brackish zone. The simulated results indicate another freshwater

605   reservoir that extends oceanward of site M29. This reservoir has a sharp upper boundary that is

606   seaward dipping in correlation with the sedimentary bedding. The salinity gradually increases with

607   depth and distance offshore. This shallow body is preserved by near-surface low permeability

608   intervals. The most distal regions of the shelf models show complete salinization of all emplaced

609   freshwater. There is a broad region of fluid concentration that is just below ocean salinity.

610

611   The numerical simulations with the high onshore-offshore connectivity model display similar

612   concentration distributions as described in the previous paragraph. The results are shown in Figure

613   15. In general, the proximal region of the shelf appears to undergo more freshening during the

614   recharge phase in all scenarios. Thick sand intervals in the HC model facilitate more advective

615   flushing with freshwater during the recharge phase. However, while the present day distributions

616   are broadly similar to the LC model, downward fingering of saline pore fluid results in more

617   compartmentalization of the seaward dipping fresh interval. Key differences are observed in the

618   the ETD scenario, where the proximal region of the model domain (0 km – 40 km) is completely

619   freshened during the recharge phase.

620
621 *Figure 14 Low onshore-offshore connectivity model showing pore fluid concentration at the end of the recharge phase (left) and*
622 *present day (right) for simulated scenarios: (a) Base case, (b) cemented intervals, (c) enhanced terrestrial discharge, (d) - (e)*
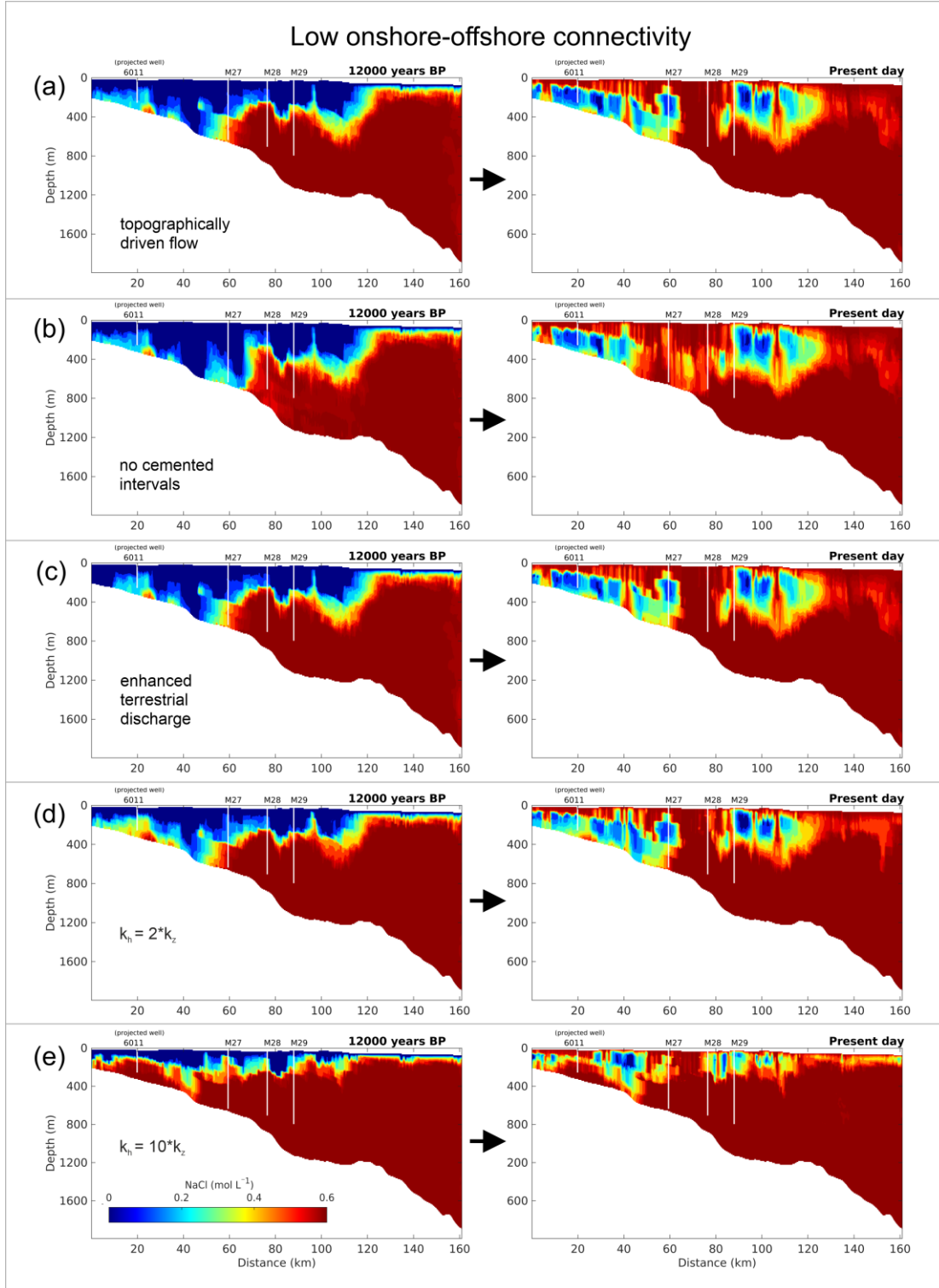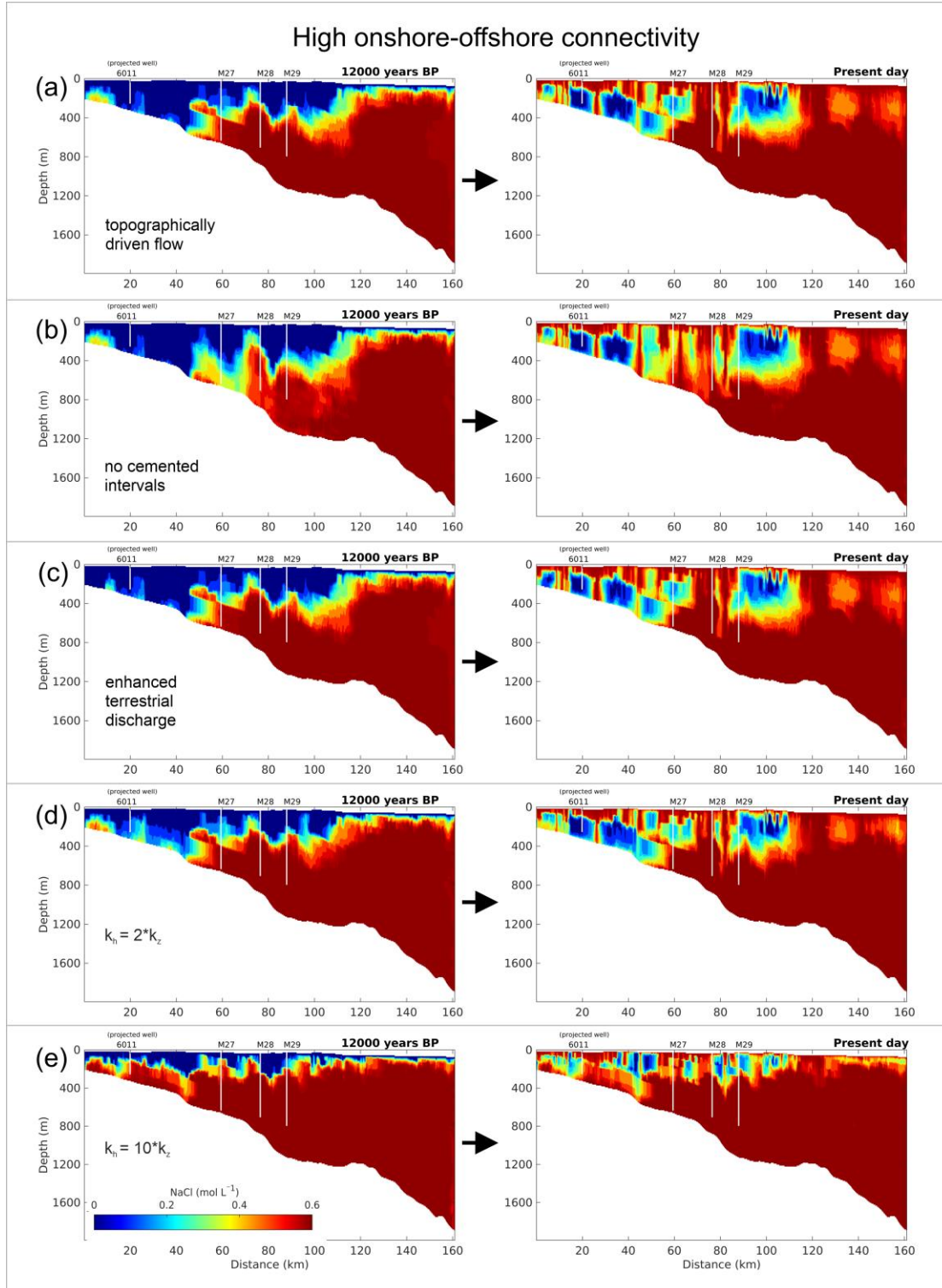623 *anisotropic permeability.*

624
625 *Figure 15 High onshore-offshore connectivity model showing pore fluid concentration at the end of the recharge phase (left) and*
626 *present day (right) for simulated scenarios: (a) Base case, (b) cemented intervals, (c) enhanced terrestrial discharge, (d) - (e)*
627 *anisotropic permeability.*

628   Borehole pore fluid concentration profiles
629
630   Figure 16 shows the pore fluid concentration profiles extracted at the four well locations in both

631   model realizations. A close fit between simulated and measured data is observed at site 6011 in

632   both cases. All scenarios closely match the measured concentration with the exception of the high

633   anisoptropic ratio. In the HC model, the profiles show lower concentrations compared to the LC

634   model, consistent with increased offshore directed flow of freshwater from the landward boundary.

635

636   At M27 there are two major freshwater intervals, an upper reservoir between 200 m – 400 m with

637   sharp boundaries, and a shallow interval characterized by a sharp upper boundary and gradually

638   increasing pore fluid concentration with depth. The upper reservoir is replicated with slightly

639   higher solute concentrations in both model realizations. In the case of high anisotropy and the

640   absence of cemented intervals, both models do not capture this upper reservoir. In the case of high

641   anisotropy, this reservoir is not freshened during the LGM (see Figure 14). In the absence of

642   cemented intervals we observe a salinization of the entire sediment column in the region of M27.

643   The lower reservoir is not reproduced in any of the modelled scenarios.

644

645   At well site M28, there is a stronger differentiation between the HC and LC models. The HC model

646   shows a fresh – brackish interval in the shallow part of the well (< 300 mbsf) in all scenarios,

647   which is consistent with the trend of the measured data. The LC model consistently over-estimates

648   the salinity in this region of the model. Given the close fit between the HC and LC models at the

649   more proximal M27, this misfit at M28 can be attributed to the differences in surface-connected

650   pathways in the two models rather than onshore-offshore connectivity (see Figure 12). The fresh –

651   brackish interval in the deeper section of the well is not reproduced exactly at the well location.

652   However, in the region around M28, both models show some brackish pore fluid down to ~500 m

653   (see Fig. 14).

654

655   The concentration profiles at site M29 closely match across all scenarios. The simulated results

656   generally represent the trend of the observed data, with a broad fresh – brackish zone in the upper

657   section of the well. The alternating fresh – saline intervals have been attributed to thin shale beds

658   on the centimetre scale (Mountain et al. 2010), which are below our model resolution. In the deeper

659   section of the well we observed some hyper-salinization of the pore fluid with a brine developing

660   at ~700 mbsf.
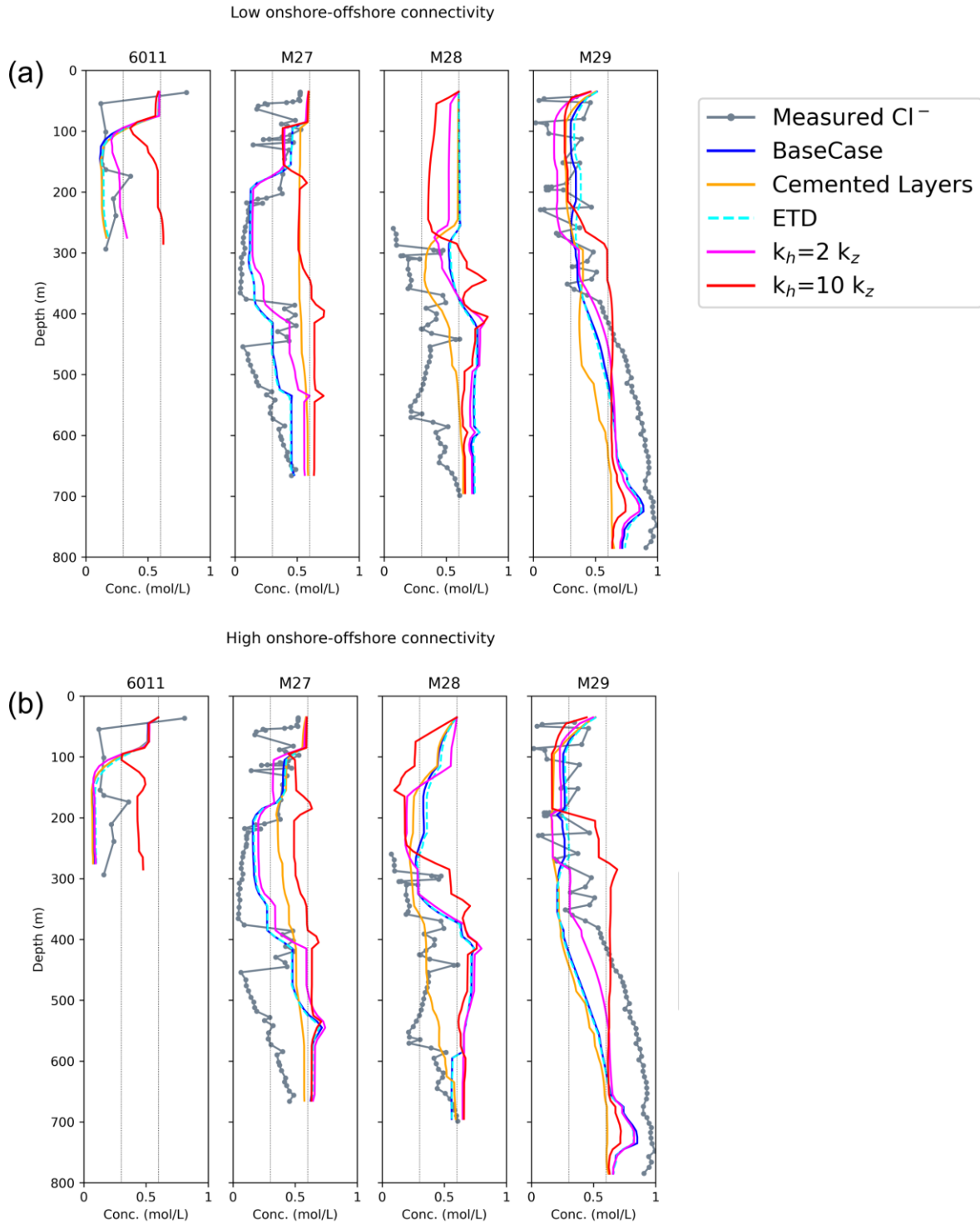
661

662
663   *Figure 16 Comparison between measured pore fluid concentration and simulated concentrations at 4 well locations in the model*
664   *domain. The low onshore-offshore connectivity model is shown in (a) and high onshore-offshore connectivity model.*

3.1.3 Paleo-hydrological reconstruction on a representative shelf model

This section presents the results of simulating conditions over the past 70 000 years until present day, with a plausible combination of scenarios on a single representative model. Based on the probability distribution of the suite of models (see Figure 5), we select the low onshore-offshore connectivity model as the representative case.

The transient simulation results are shown in Figure 17 for the isotropic permeability case. The simulated present-day distribution shows a laterally extensive system of offshore freshened groundwater with geometries correlating to the stratigraphic sequence boundaries on the shelf. Surviving freshwater intervals are generally oceanward dipping with sharp upper boundaries. Three main reservoirs can be identified in the present-day distribution (Figure 17 d). A thick interval of freshwater extending from the landward boundary to about 40 km offshore (labelled R1). In the region of site M27, a second freshwater reservoir is preserved by cemented and low-permeability layers (labelled R2). Downward fingering of saline pore fluid around 40 km in the model domain disconnects this reservoir from R1. Another laterally extensive zone of preserved freshwater extends about 30 km oceanward from site M29 and becomes gradually more saline – R3. This reservoir also appears to be compartmentalized by downward fingering saline pore fluid. The more distal region is characterized by a relatively well mixed zone of pore fluid just below seawater concentration.

683

684 *Figure 17 Simulated pore fluid concentration on a geologically heterogeneous 2D model of the New Jersey shelf. Progressive*
685 *salinization of emplaced groundwater is shown from the onset of the marine transgression 12 000 years ago (top left) to the present-*
686 *day (bottom right). The surviving freshwater reservoir system is laterally extensive but compartmentalized by downward fingering*
687 *of saline pore fluid via discontinuities in confining layers.*

688   The results show that downward fingering of saline pore fluid during transgression occurs via

689   seafloor-connected pathways. The denser fluid begins to diffuse laterally when low-permeability

690   or cemented layers are encountered. This can lead to the observed alternating fresh and saline pore

691   fluid intervals. The transient results of the transgressive period for the anisotropic permeability

692   scenario (k_h=2k_z) are shown in Figure 18. The general observations are consistent with the isotropic

693   case. However, R1 and R2 are now separated by a zone of brackish pore fluid. The preserved
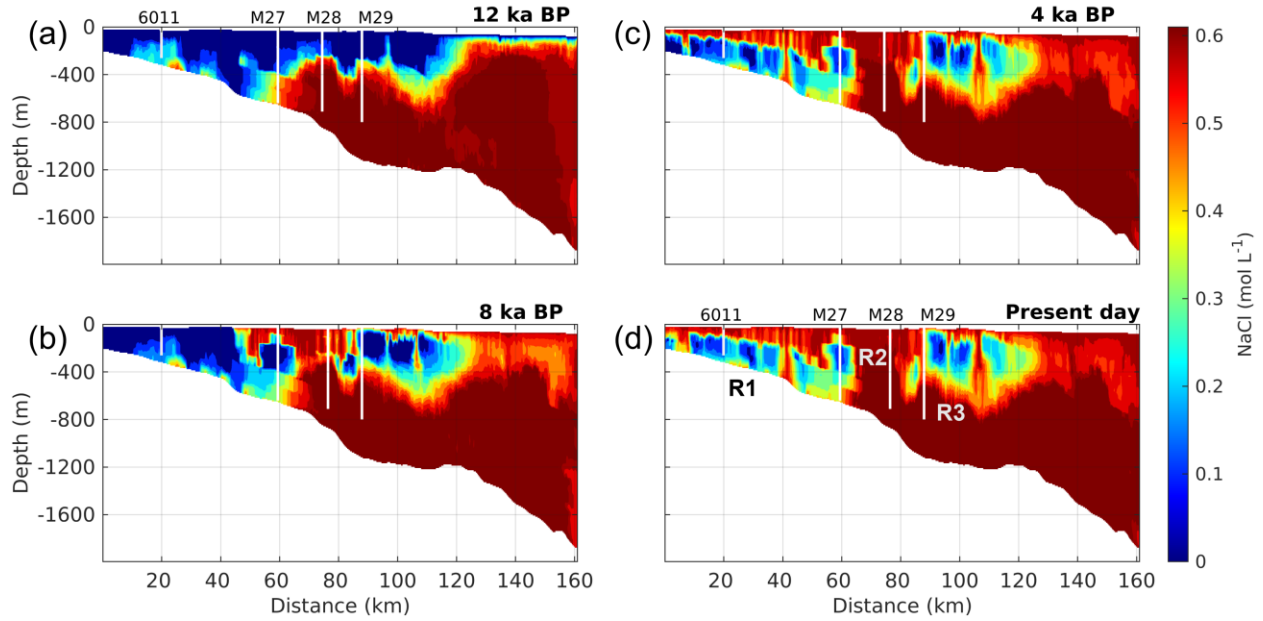
694   intervals are marginally thinner in the presence of anisotropy.

696   *Figure 18 Simulated pore fluid concentration on a geologically heterogeneous 2D model of the New Jersey shelf with anisotropic*
697   *permeability where $k_h=2k_z$. Progressive salinization of emplaced groundwater is shown from the onset of the marine transgression*
698   *12 000 years ago (top left) to the present (bottom right). The surviving freshwater reservoir system is laterally extensive but generally*
699   *thinner than the isotropic permeability scenario.*

700   The volumetric trend shown in Figure 19 a, shows that although more freshwater recharge is

701   emplaced during the isotropic permeability scenario, the surviving fresh water volumes are

702   effectively the same. The system shows a net increase in the volume of freshwater that is stored

703   over the regressive – transgressive cycle.

Figure 19 Summary of key metrics for two simulated paleo-reconstructions: enhanced terrestrial discharge (ETD) with isotropic permeability (green), and ETD with $k_h=2*k_z$ (blue) (a) Freshwater volumetric curve for the paleo-reconstruction of the LGM on the representative 2D New Jersey shelf model. The shaded blue region shows the difference between the initial assumed volume of freshwater in the model domain and the present-day volume, highlighting the net increase in freshwater storage. (b) Comparison of measured and simulated concentration profiles at the borehole locations in the model domain. Blue curve shows the low-anisotropic permeability scenario, and the green curve shows the isotropic scenario.

Simulated concentration profiles were compared to measured values at the well locations shown in Figure 19 b. At site 6011, both simulated profiles closely match the measured data. The freshwater preserved just below the seafloor in the measured data is not captured by the model. At site M27 both scenarios reproduce the main freshwater interval (200 m – 400 m) with marginally higher

715   concentration. However, the deeper reservoir was not captured by the model. Once again, the

716   preserved freshwater just below the seafloor is not reproduced. At site M28, the models

717   underestimate the amount of freshwater stored in the sediment column. However, more freshwater

718   is preserved a few kilometres oceanward of this site. At site M29, the trend of the shallow multi-

719   layered freshwater system is broadly captured down to approximately 350 m. Below this depth,

720   the modelled salinities systematically underestimate the measured values, which might be

721   influenced by buried evaporites. However, some degree of hyper-salinization is observed.

722

723 **4   Discussion**

724 The simulation results provide detailed insight regarding the importance of geological

725 heterogeneity for the emplacement and subsequent preservation of freshwater into the sediments

726 of the New Jersey shelf. The numerical analysis provides strong evidence that the hydrogeologic

727 conditions on the shelf during the LGM, together with the sequence stratigraphic architecture can

728 lead to a complex layered OFG reservoir system. We employed a stochastic modelling approach

729 using the sequential indicator simulation (SIS) to populate the model domain with sand, silt and

730 shale facies. The variogram based approach is capable of sufficiently representing the sedimentary

731 patterns of the passive margin depositional setting on the shelf. That is a key consideration when

732 choosing a modelling approach   (Seifert and Jensen 1999). An extended discussion on the

733 suitability of SIS for a 2D model of the New Jersey shelf is presented in Thomas et al. (2019).

734 Additionally, our approach incorporates geological information in the form of stratigraphic

735 boundaries interpreted on seismic data, and trends derived from borehole data. This has been

736 shown to reduce uncertainty in geostatistical models (Labourdette et al. 2008)

737 The Monte Carlo sampling of stochastic realizations allowed us to rank the models based on a key

738 system characteristic, i.e., onshore-offshore connectivity. This allows for the selection of

739 appropriate realizations from the probabilistic model. Analysis of dynamic response data is a

740 common way to reduce uncertainty in stochastic facies models as it carries information about flow

741 connectivity in the model domain (Hill and Tiedeman 2006). Each model realization honours the

742 available data and thus represents equally likely scenarios. It must be noted that the probability

743 distribution obtained is a function of the specific conditions assigned to the suite of models. The

744 conditions applied in this study were designed specifically to quantify the distribution of onshore-

745 offshore connectivity in the suite of models. This approach can be adapted in future studies to

746 investigate other components of OFG systems such as confining layer continuity.

747 **4.1   What drove freshwater emplacement on the New Jersey shelf?**

748 Our numerical study shows that periods of rapid sea-level fall during the LGM accelerated the

749 flushing of shelf sediments with freshwater via meteoric recharge. During the period of relatively

750 slow regression, the observed freshening trend is considerably flattened. The correlation between

751 rapid sea level fall and increased recharge was persistent across all simulated scenarios. All other

752   influences were superimposed on this trend. This observed dynamic supports the hypothesis that
753   sealevel fall drives vigorous freshwater flow toward the open ocean (Meisler et al. 1984). Previous
754   numerical studies of OFG systems have shown the infuence of sealevel lowstand on freshwater
755   emplacement (Micallef et al. 2020; Person et al. 2003) . However, our results highlight the
756   particular influence of rapid rate of sea level fall. In general, the depth of freshwater recharge
757   increased inland with surface elevation. A 3D numerical study of the US mid-Atlantic shelf by
758   Siegel et al. (2014) highlighted the strong control of seafloor topography on fresh groundwater
759   emplacement. On average, observed salinities were lower in the relatively elevated eastern region
760   of their model over the simulated period. The New Jersey shelf has a gentle gradient, however it
761   is not consistently seaward sloping. Ocean floor bathymetry shows a slightly elevated region just
762   beyond the mid-shelf, 100 km from the coastline. This local topographic high corresponds to a
763   deeper circulation of freshwater during the low-stand period in all scenarios considered. This is
764   consistent with observations in a regional study by Siegel et al. (2014), where seafloor topography
765   was shown to be responsible for convection cells driving the re-distribution of fresh and saline
766   water to a depth of several hundred meters. In a study characterizing global offshore fresh
767   groundwater reservoirs, Zamrsky et al. (2020) showed that the topographic profile of the shelf is a
768   key characteristic governing the emplacement of freshwater in the system. These findings together
769   suggest that localized topographic variations on the seafloor should be considered as important
770   features, with a high likelihood to coincide with OFG in regions where the appropriate paleo-
771   hydrologic conditions existed.

772   The extent of freshwater recharge varies across the four well sites. The sediment column in the
773   most proximal part of the model near the projected location of well 6011 is completely freshened
774   in every scenario. Most of the sediment column in the region of M27 is freshened, with brackish
775   pore fluid remaining below 400 m in the well. The salinity distribution at the end of the recharge
776   phase indicate that freshening occurs by top-down as well as lateral flow of freshwater from the
777   landward direction. At site M28 and M29, freshening occurs down to a maximum of 300 m, the
778   deeper sediments remain relatively saline across all scenarios. Freshening in this region appears to
779   primarily occur by top-down meteoric recharge via surface-connected pathways. The model shows
780   that the LGM is not sufficient to freshen the deeper reservoirs that have been observed at sites M27
781   and M28. The deep freshwater intervals at those wells are either relics of a previous interglacial
782   period, or recharge via 3D flow pathways not captured in this study.

783   The offshore extent of freshening in our model is consistent with an earlier regional numerical

784   study of the Pleistocene glacial maximum on the US Atlantic margin by Cohen et al. (2010). That

785   study also reported freshwater emplacement at distances up to 100 km from the modern-day

786   coastline. They attributed this to offshore directed flow in shallow outcropping Miocene sands.

787   The layered regional model considered by Cohen et al. (2010) did not account for the presence of

788   discontinuities in confining layers. The lateral heterogeneity in our model captures this important

789   component of the recharge process, highlighting the importance of incorporating realistic

790   geological features when characterizing OFG systems. Recharge is not strictly confined to the

791   inland outcrops of sandy units, rather it occurs all across the shelf transect driven by the

792   topographic gradient and controlled by the sequence stratigraphic architecture. Our simulations

793   consider both low- and high onshore – offshore connectivity scenarios. These clearly show that

794   in the presence of geological heterogeneity, offshore-directed flow does not translate to increased

795   freshwater emplacement in the distal shelf region. This implies that offshore-directed flow, due to

796   terrestrial drivers such as over-pressure induced by ice-sheet loading, are not an absolute

797   requirement for emplacement of freshwater in sediments that are currently far offshore.

798   Previous numerical studies showed that increased advective forces which drive sub-glacial

799   freshwater emplacement do not extend far beyond the edge of the ice sheet (Cohen et al. 2010;

800   Siegel et al. 2014). Results obtained on this New Jersey transect of enhanced terrestrial discharge

801   are consistent with this dynamic system behavior. An elevated hydraulic head at the inland

802   boundary only affected the salinity observed in the proximal part of the model, while the overall

803   emplaced volume of freshwater increased only marginally in response to an increased hydraulic

804   head of 25 m at the inland boundary. This value was chosen to represent a high end member value

805   of enhanced terrestrial discharge based on regional reconstructions presented in Cohen et al.

806   (2010), which showed elevated heads of 30 m – 40 m during the Pleistocene lowstand in the region

807   onshore New Jersey shelf. This constant head value represents an estimate of potential offshore

808   directed flow. Actual values of offshore groundwater discharge are irregular and vary with time

809   (Burnett et al. 2006).

810   The most significant change in the volume of freshwater occurred when anisotropic permeability

811   was implemented. An anisotropic ratio of ten resulted in an observable change in the shape of the

812   freshwater – saltwater interface. These results suggests that the downward percolation of

813 freshwater into the sediment column via surface connected pathways is a crucial mechanism for
814 freshwater emplacement. Notably, the reduction in freshwater recharge was smaller in the HC
815 model. This we attribute to the higher lateral connectivity relative to the LC model, which allows
816 more freshwater into the sediments. However, in the case of higher anisotropy both models result
817 in similar volumes of recharge. This highlights again the importance of surface derived recharge.
818 Meisler et al. (1984) found that a lower anisotropy ratio resulted in a landward as well as downward
819 shift of the sharp interface position in their layered shelf model. This basic correlation is observed
820 in our results; however, the response is considerably more dynamic in the heterogeneous shelf
821 model. The implementation of a low anisotropy ratio of two, resulted in a closer fit to the observed
822 data. This suggests that the system can be characterized by low to moderate permeability
823 anisotropy. Our study highlights the importance of constraining permeability anisotropy in the
824 characterization of OFG systems. Anisotropy can be identified via specialized laboratory
825 measurements on core plugs (Crawford et al. 2008). Such an approach can improve model
826 constraints. However, upscaling to the field scale is a non-trivial part of incorporating this
827 information into flow models, which is dependent on the geological heterogeneity (Menke et al.
828 2021; Szymkiewicz 2013)

829 In the layered depositional setting of the New Jersey shelf, density instabilities occur as freshwater
830 is driven oceanward and advances non-uniformly. Preferential flow in high-permeability intervals
831 creates a complex combination of advective and diffusive processes during the lowstand period.
832 We found two key mechanisms of freshening. The primary mechanism is advective freshening
833 driven by the oceanward hydraulic gradient. This causes freshwater to flow preferentially into
834 high-permeability sediment layers, flushing out the salt water. Density instabilities occur where
835 aquifer units are freshened while overlying confining units remain saturated with denser saline
836 pore fluid for a longer period. In the early stages of recharge, this juxtaposition results in sharp
837 salinity contrasts between aquifers and overlying confining units. This contrast gives way to the
838 secondary mechanism, convective mixing, resulting from the unstable concentration gradients in
839 the layered sedimentary setting. Denser saline pore fluid in confining layers fingers downward into
840 freshened intervals, while more buoyant freshwater migrates upward. The temperature gradient on
841 the shelf likely contributes to the buoyancy of freshwater driven deeper into the sediment column.

4.2 Marine transgression and freshwater survival

Kooi et al. (2000) conducted a numerical study analyzing the various modes by which seawater intrusion occurs during a marine transgression. Their study identified four modes: (1) horizontal intrusion in the case of a slow transgression, (2) vertical intrusion by seawater fingering during rapid transgression over a highly permeable medium, (3) vertical intrusion by diffusion for rapid transgressions over a low-permeability medium, and (4) vertical intrusion by a combination of diffusion and low-salinity fingering for rapid transgression over a layered subsurface. Kooi et al. (2000) showed that there is a critical rate of marine transgression that determines whether a transition occurs from horizontal to one of the vertical intrusion modes. The marine transgression that took place after the last glacial maximum can be considered as above critical for the low-angle New Jersey shelf. The 161 km model domain proceeded from sub-aerial exposure to complete inundation with ocean water in approximately 12 000 years from the LGM to the present day. This corresponds to a transgression rate of approximately 13 m per year. Based on the results obtained in this study, there is evidence for three vertical modes of intrusion associated with the rapid transgression. In the distal region of the shelf, where low-permeability facies are dominant, a seaward dipping wedge of low-salinity pore fluid develops during the transgression. In the mid-shelf region, low-permeability intervals near the ocean floor preserve a substantial amount of fresh water, however, downward fingering of saline fluid through overlying shales create lateral salinity variations in the reservoir (R3). This results in a broad and relatively well-mixed transition zone on the oceanward end of this reservoir. The landward part of R3 is characterized by sharp boundaries between freshwater intervals and saline pore fluid in overlying confining layers (see Fig. 17). In the more proximal region of the shelf, the permeability distribution trends towards more high-permeability sands, where a different mode can be observed. This mode is characterized by downward fingering ocean water creating a high-salinity pore fluid columns, which compartmentalize the surviving freshwater body (Fig. 17 and 18). A field study of vertical seawater intrusion on a freshwater lens by Post and Houben (2017) showed that downward fingering of saline pore fluid was the dominant driver of mixing. Groen et al. (2000) showed how this downward fingering process can speed up the salinization of sequestered freshwater on the continental shelf. Our stochastic New Jersey shelf model accounts for discontinuities in the overlying confining units, and thus highlights the importance of geological heterogeneity on the survival of offshore freshened groundwater. Future numerical studies, for example in 3D, can

873 benefit from considering the various modes of intrusion that generated by the subsurface
874 heterogeneity and underlying regional permeability trends. The 2D approach presented in this
875 study does not account for all potential flow pathways.

876 The present-day scenario consisting of a layered and compartmentalized fresh-brackish water zone
877 results from connected pathways between the ocean and deeper, permeable sediments. Along these
878 pathways, density-driven flow salinifies most permeable units, while cemented and low-
879 permeability intervals shield some freshwater reservoirs from above. These findings support the
880 salinification mechanisms suggested by Lofi et al. (2013) for mid-shelf reservoirs based on a
881 qualitative shelf model. These authors postulated that either outcropping reservoirs at the seafloor,
882 or a pathway of intermediary connected reservoirs could explain the salinization of the mid-shelf
883 region. Our numerical simulations favor the latter of these two explanations. Lateral heterogeneity
884 results in complex, connected pathways between the ocean and deeper reservoirs of emplaced
885 freshwater. This is consistent with earlier simulations of surviving freshwater body in a
886 heterogeneous shelf model presented by Thomas et al. (2019), in which authors showed that the
887 observed salinity distribution is strongly influenced by the stratigraphic architecture. As we
888 address this problem only in 2D, the full complexity and influence of such pathways cannot be
889 entirely captured. In a 3D model, ocean water can enter reservoirs from multiple directions,
890 resulting in different survival rates for freshened reservoirs. However, considering that
891 depositional environment for Miocene sediments has been identified as wave-dominated
892 (Monteverde et al. 2008; Proust et al. 2018), we postulate that the complexity of the groundwater
893 flow and solute transport on New Jersey shelf is largely a function of dip-oriented variation in
894 sediment properties. Based on the principles of a wave-dominated environment, it can be assumed
895 that there is considerably less variation in sediment properties in the shoreline parallel direction.
896 The 2D model thus provides a representative perspective on the dynamic life cycle of offshore
897 freshened groundwater in the New Jersey passive margin setting.

898 **4.3   Modern or Fossil Water?**

899 The results of our numerical study can be discussed in the light of the two main hypotheses
900 proposed for explaining the presence of freshwater offshore New Jersey. The first hypothesis
901 identifies the source as meteoric and sub-ice-sheet recharge during the sea-level lowstand

902   associated with the last glacial maximum or potentially earlier periods (Cohen et al. 2010; Kooi

903   and Groen 2001; Person et al. 2003; Siegel et al. 2014). Results presented in this study show that

904   both high- and low-permeability sediments of the New Jersey shelf were flushed with freshwater

905   during the LGM in all scenarios considered. At the expedition 313 well sites in the mid-shelf

906   region, we observed freshening of the shallow reservoirs, consistent with present-day observations.

907   However, deeper reservoirs in M27 and M28 remained relatively saline during the simulated

908   period. In the subsequent transgressive period, these reservoirs underwent partial salinification,

909   but a significant portion of fresh – brackish water survives to the present day. This observation

910   supports the hypothesis that freshwater sampled at Expedition 313 sites would be fossil water

911   emplaced via meteoric recharge during the LGM. Our simulations suggest that the deeper

912   reservoirs in M27 and M28 may even pre-date the LGM. An alternative explanation for these

913   reservoirs is that they were recharged via shoreline parallel connected flow pathways, which our

914   2D model does not capture. It is plausible that a full 3D characterization of the shelf would result

915   in the freshening of these deeper reservoirs during the LGM.

916   To date there have been no published studies on the absolute ages of groundwater sampled at the

917   Expedition 313 sites. In an earlier coastal aquifer study, McAuley et al. (2001) analysed radioactive

918   isotopes in four wells in order to estimate groundwater ages in the coastal Atlantic City 800-foot

919   sand, the principal source of water supply for southern New Jersey coastal communities. Their

920   transect extended from inland to approximately 8.5 km offshore. At the Pleasantville well site, 1.6

921   km inland of the coastline, sampled water was dated at 17 950 years BP. The two offshore sites

922   yielded ages of at least 22 000 years BP and possibly older than 30 000 years BP. These dates

923   support the hypothesis of Pleistocene freshwater emplaced in the mid-shelf reservoirs. As a caveat,

924   van Geldern et al. (2013) reasoned that these dates may be over-estimated, as it cannot be verified

925   whether the relevant correction models were used in the calculation of the radiocarbon ages.

926   Despite not providing information on absolute ages, stable isotope ratios of oxygen and hydrogen

927   in water were used as natural tracers to characterize the origins and composition in both marine

928   and terrestrial studies (Bigg and Rohling 2000; Bowen and Wilkinson 2002; Dutton et al. 2005;

929   Maslin and Swann 2006). van Geldern et al. (2013) analysed the stable isotope composition of

930   Expedition 313 samples. They concluded that the freshwater was either of modern meteoric origin

931   and therefore rapidly recharged, or it pre-dates the Pleistocene and had been recharged during a

932   period with similar climatic conditions to modern times. $\delta^{18}O$ values of water sampled at

933   Expedition 313 sites range between -0.8 ‰ and -7.0 ‰, indicating a mixture of modern meteoric

934   recharge and seawater as the source of pore fluids (van Geldern et al. 2013). Water of Pleistocene

935   age would normally be characterized by a comparatively lower range of isotope values (Mook and

936   Rozanski 2000): $\delta^{18}O$ values in the range of -11 ‰ to -18.0 ‰ were reported for Pleistocene-age

937   recharge in the Cambrian-Ordovician aquifer of Iowa, further inland on the North American

938   continent (Siegel 1991). However, an isotopically depleted body of Pleistocene water was shown

939   there to be caused by a dilution of a combination of glacial meltwater and precipitation. This

940   diluted water mass was deep in the aquifer, below 300 m of confining layers, and $\delta^{18}O$ values are

941   within the range of modern precipitation for Iowa (from -11 to -6.0 ‰) (Siegel 1991). This

942   regional setting of the sample locations analysed by Siegel (1991., Fig. 2) is analogous to the New

943   Jersey case, which had not been covered by ice-sheets as it was rather proximal to the edges of

944   their southern-most advance (Cohen et al. 2010). The depleted isotopic signature of the Pleistocene

945   groundwater suggests that the climate at the end of the last glacial period was mild. This conclusion

946   is also supported in multi-disciplinary studies (Hanshaw et al. 1979; Morgan et al. 1987). These

947   studies provide strong evidence that groundwater isotope values similar to that of modern

948   precipitation do not unambiguously indicate recent recharge.

949   Our simulation results do not support any significant role of modern recharge in the persistence of

950   the mid-shelf freshwater system observed by IODP Expedition 313 (Mountain et al. 2010).

951   Previous studies have shown that in certain geological settings, an active recharge of offshore

952   freshened groundwater reservoirs can occur (Michael et al. 2016; Varma and Michael 2012). Our

953   stochastic approach considered both high and low onshore-offshore connectivity scenarios and

954   found only marginal changes in present-day freshwater distrbutions at the most proximal regions

955   of the model domain (i.e., well site 6011). Observed profiles at IODP expedition 313 sites are

956   unaffected by offshore directed discharge. A more speculative hypothesis suggests that the

957   freshwater may date back to the Miocene age (Meisler et al. 1984). In a study of groundwater

958   residence times in the Alberta Basin Gupta et al. (2015) performed simulations constrained by

959   hydrogeologic and geochemical observations. The results showed dilution of old pore fluids

960   occurred due to flushing by younger waters. The hydrogeologic model presented in this New

961   Jersey study shows that significant flushing of the mid-Miocene sediments likely occurred during

962 the last glacial maximum. This exchange and mixing of pore fluid likely occurred in multiple

963 glacial – interglacial cycles and can therefore influence the age of pore fluid determined solely by

964 geochemical methods. Our numerical results strongly suggests that water emplaced before the

965 Pleistocene would have likely been flushed out since, and consequently, its signature would have

966 been over-printed by relatively younger groundwater, as speculated by Meisler et al. (1984).

967

968 The results of this study are broadly consistent with the salinity profiles of the multi-layered

969 reservoir system of offshore freshened groundwater observed in IODP Expedition 313 (Mountain

970 et al. 2010) and the projected position of AMCOR well site 6011. Portions of the surviving

971 freshwater in our numerical simulations are also consistent with the resistivity anomalies identified

972 by an independently conducted electromagnetic survey of the US continental shelf by Gustafson

973 et al. (2019). In the proximal region of the shelf, Gustafson et al. (2019) considered the strong

974 resistivity anomaly as evidence for an active connection between onshore and offshore freshwater

975 reservoirs. However, numerical simulations show that offshore directed only influences the

976 freshwater in the most proximal region of the model (i.e., within 20 km from the landward

977 boundary). Downward fingering ocean water compartmentalizes the surviving freshwater system

978 into isolated, hydraulically disconnected pockets as discussed earlier. In both high and low

979 onshore-offshore connectivity scenarios, the offshore directed discharge is insufficient to maintain

980 open freshwater conduits to the surviving reservoirs in the mid-shelf region. Figure 20 shows a

981 visual comparison between the resistivity anomaly and our paleo-reconstruction on both high and

982 low connectivity model scenarios. Our model domain was clipped, and color scales were adjusted

983 to match the presented resistivity data. There is a reasonably close fit between the resistivity

984 anomalies and the simulated freshwater distribution. The proximal body of freshwater preserved

985 in our model is consistent with the seaward dipping resistivity anomaly presented by Gustafson et

986 al. (2019). However, our heterogeneous model domain captures lateral variability in pore fluid

987 concentration resulting from downward fingering via seafloor-connected pathways. This

988 downward fingering is more pronounced in the high onshore-offhshore connectivity model, as it

989 features thicker high permeability intervals that more readily facilitate downward fingering. A

990 numerical study of aquifer vulnerability to ocean storm surges by Cardenas et al. (2015) found that

991 while zones of downward fingering saline pore fluid were apparent in their numerical model

992 results, there was only tentative evidence of their existence in the geophysical field measurements.

993   Electromagnetic methods integrate resistivity over volumes which become larger with increasing

994   depth. Therefore, small-scale signatures at greater depth, such as the saline fingers are not resolved.

995   Finally, the shallow anomaly in the mid-shelf region, which gradually fades in the oceanward

996   direction is similar to the preserved freshwater reservoir earlier described as R3. This reservoir has

997   the lowest salinity in the region of M29 and gradually becomes more saline in the oceanward

998   direction, consistent with the trend of the anomaly.

999

1000   Figure 20 shows a qualitative comparison between independent datasets. Future studies can benefit

1001   from integrating numerical flow simulations into a process-based inversion scheme to improve

1002   constraints of subsurface properties such as hydraulic conductivity or porosity (Wagner and

1003   Uhlemann 2021). A stochastic approach to capture geological heterogeneity, as presented in this

1004   paper, can produce more geologically representative constraints on porosity distribution, which

1005   strongly influences the interpretation of resistivity data. Additionally, structurally constrained

1006   inversion can integrate known stratigraphic features, such as cemented intervals, into geophysical

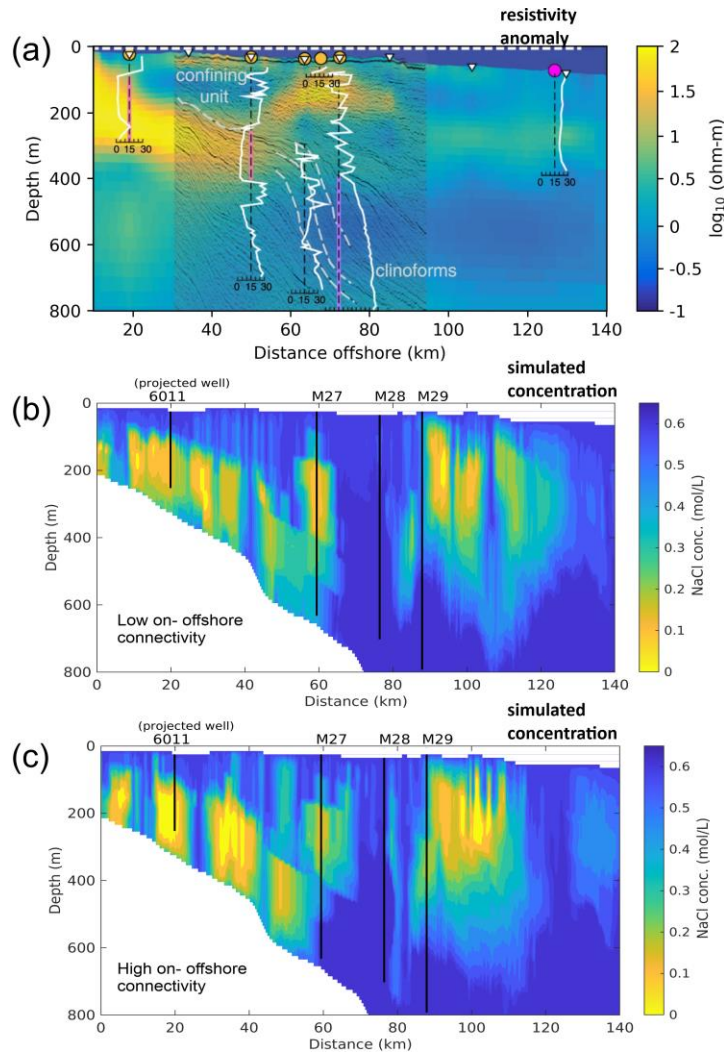1007   data processing as detailed by Wagner and Uhlemann (2021).

1008
1009 *Figure 20 Visual comparison of resistivity anomaly reporty by Gustafson et al. (2019) and numerical simulation results of our paleo-*
1010 *hydrological reconstruction of the LGM on the New Jersey shelf. (b) and (c) show the low and high onshore – offshore connectivity*
1011 *scenarios, respectively. Both results show freshwater distribution that is broadly consistent with the observed resistivity anomaly.*
1012 *Future studies can benefit from joint or process based inversion of resistivity data to better constrain the characterization of OFG*
1013 *systems.*

1014   Based on the evidence of this numerical study, and previous findings discussed earlier, we

1015   conclude that the freshwater system had been almost completely recharged during the lowstand

1016   period associated with the last glacial maximum beginning at least 70 000 years ago. Although not

1017   studied here, it can also be safely assumed that some partial recharge into the sediments also

1018   occurred prior to 70 000 years ago. Therefore, the observed freshwater system is slowly shrinking

1019   due to diffusion and density-driven flow through connected pathways to the ocean. This

1020   observation does not account for the 3D effects of laterally connected pathways that can likely

1021   alter the observed distribution. The net increase in freshwater stored on the New Jersey shelf over

1022   the simulated period suggest that the cyclical flushing and re-salinization of shelf sediments, which

1023   takes place over glacial – interglacial cycles is an asymmetrical process. This means that some

1024   portion of the freshwater recharged into the system during glacial sea-level lowstands will likely

1025   survive the typical inter-glacial period and thus the system favours storage of freshened pore fluid

1026   over geological time-scales. A numerical study of freshwater survival on the New Jersey shelf by

1027   Thomas et al. (2019) also found that at least 15 % of initially assumed freshwater volume had

1028   survived after simulating 30 000 years of ocean coverage.

1029   **4.4   Resource perspective**

1030   We present some simple back-of-the-envelope calculations based on the paleo-reconstruction

1031   presented in this study. The volume of freshwater in this case was approximately 0.54 km^3. The

1032   model cell width of 100 m means this can be expressed as a potential storage of 5.4 km^3 of fresh-

1033   to-brackish water per kilometer of the New Jersey coastline. This is more than a previous estimate

1034   of 3.8 km^3 of freshened groundwater per kilometer of coastline presented in a study by Cohen et

1035   al. (2010), which was an average value based on data from four different continental shelf

1036   transects. The value presented by Cohen et al. (2010) is based on an effective sediment porosity of

1037   20 %. The estimate presented in this study is directly related to the New Jersey case of relatively

1038   unconsolidated sediments on a passive margin setting, with porosity ranging from 40 % to 60 %.

1039   Extrapolating these results along 180 km of the New Jersey coastline, we estimate about 1 000

1040   km^3 of fresh to brackish water to exist under present-day conditions on the shelf. A comparable

1041   value of 1 300 km^3 of freshwater was estimated to be sequestered in continental shelf reservoirs in

1042   New England, US (Cohen et al. 2010). To put this into perspective, the daily groundwater water

1043   extraction in entire United States, was estimated at 73 km^3 in 2010 , based on an extraction rate of

1044   0.2 km^3 / day (Maupin et al. 2014).

1045   The New Jersey shelf is only one of several occurrences of extensive systems of offshore

1046   freshened groundwater (Micallef et al. 2020a). As the understanding of these systems continues to

1047   expand, an important next step is the characterization of offshore fresh groundwater reservoirs.

1048   The results of this study on a representative geological model highlight the complex and dynamic

1049   interplay of topography, sediment heterogeneity, and anisotropy of permeability. These factors

1050   appear to have systemic effects on the volume of freshwater emplaced during low-stand periods

1051   as well as the survival and storage of this freshwater during subsequent transgressive periods. The

1052   characterization of offshore freshened groundwater requires dedicated hydrogeological data

1053   acquisition and analysis for deciphering the complex history of these reserves and characterizing

1054   their resource potential.

5   Conclusions

1056   Integrating realistic heterogeneity based on seismic and well data can explain the multi-layered

1057   freshwater system on the New Jersey shelf. A geologically representative model shows that the

1058   OFG system is laterally compartmentalized by downward fingering saline fluids through

1059   connected pathways to the ocean. This shows that the accurate modelling of offshore fresh

1060   groundwater reservoirs requires adequate characterization of the geological heterogeneity. Our

1061   sensitivity analysis shows surface derived meteoric recharge is the primary mechanism for

1062   freshening of the sediment column during sealevel lowstand. Surface connected pathways and

1063   permeability anisotropy are therefore fundamental characteristics of the New Jersey shelf OFG

1064   system.

1065   By using a stochastic modeling approach to generate high and low onshore-offshore connectivity

1066   scenarios, we show that terrestrial discharge is not responsible for the freshwater intervals

1067   observed at Expeditions 313 well sites. Meteoric recharge during the lowstand associated with the

1068   LGM can sufficiently explain the existence of shallow reservoirs (<400 mbsf). The emplacement

1069   of freshwater was driven primarily by the topographic gradient, which caused surface recharge to

1070   infiltrate the oceanward-dipping sediments. Deeper freshened intervals at wells sites M27 and M28

1071   are either relics of a previous interglacial period, or were recharged via 3D flow pathways not

1072   captured in this study. However, the increasing salinity with depth is not consistent with a deeper

1073   freshwater source.

1074   Finally, the observed volumetric trends suggest that the cyclical flushing and re-salinization of

1075   shelf sediments that takes place over glacial – interglacial cycles is an asymmetrical process, which

1076   favours storage of freshened pore fluid. In light of present-day stressed water supply and changing

1077   climate conditions, this has implications for the consideration of these unconventional

1078   groundwater resources. While our estimates of the freshwater volume stored on the New Jersey

1079   shelf qualifies them as a potential resource, it is important to note that these reserves are stored in

1080   low-permeability intervals and are slowly shrinking due to salinization.

Acknowledgments and Data

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