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Coastal Aquifers as Major Players in Shaping Ocean Chemistry through Solute Fluxes

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Understanding the ocean’s chemical composition is essential for comprehending the carbon cycle and its impact on climate. The direct relation between the ocean’s chemical composition and calcium carbonate saturation governs the potential for carbon preservation in sediments.$^{1}$ While rivers and hydrothermal circulation have been recognized for their influence,$^{2}$ the significance of coastal aquifers has been largely overlooked. Here we show, through an investigation of coastal aquifer groundwater flow mechanisms and chemical composition, that the long-term component of submarine groundwater discharge (SGD) is the primary contributor to major element fluxes in the ocean. It predominantly adds calcium alkalinity, on behalf of sodium and potassium. Our analysis of ocean elements and isotopes budgets reveals that the fluxes associated with long-term SGD are comparable in magnitude to those of rivers. These fluxes have substantial implications for major element residence time, ultimately impacting the carbon budget and climate. Moreover, these fluxes are closely tied to changes in sea level,$^{3}$ whereby decreasing sea levels amplify solute fluxes and increasing sea levels diminish them. Consequently, these fluxes hold the potential to modulate long-term cooling and warming rates on a timescale exceeding 1000 years.

The chemistry of the ocean is governed by the transport of elements from the land to the sea through weathering, as well as the removal of these elements by consumption, adsorption, and precipitation. Although the impact of rivers and continental weathering has been well-established for several decades, recent studies have revealed the significance of other sources (Fig. 1), including mid-ocean ridge hydrothermal systems,$^{2}$ seafloor weathering of basalt,$^{4,5}$ interaction with ocean sediments,$^{6,7}$ discharges.
**Fig. 1:** An illustration of the effect of the different processes affecting ocean chemistry. Each process affects the ratios between major elements in the ocean differently, where (+) means addition to seawater, (-) means removal from seawater, (x) means no addition and no removal, and (⟳) means addition and removal by two different reactions that may balance each other. Colors refer to the same processes in the extended data, Fig. 4 as follows: (1) rivers, (2) hydrothermal circulation along mid-ocean ridges, (3) seafloor weathering (i.e., low temperature off-axis hydrothermal circulation), (4) interaction with ocean sediments, (5) carbonate precipitation, (6) long-term SGD (density-driven seawater circulation in coastal aquifers).

from subduction zone forearcs, and submarine groundwater discharge (SGD). SGD is a complex process that involves both fresh groundwater and circulating seawater (Fig. 2), with the latter accounting for the majority of the flux.

Global submarine groundwater discharge primarily consists of circulating seawater and its estimated magnitude surpasses that of global river discharge by several times (Table 1). However, the circulation of seawater involves multiple driving forces, leading to circulation mechanisms that vary significantly in terms of their spatial and temporal scales (Table 1, Fig. 2). These mechanisms range from short-term circulation driven by tides and waves, to seasonal-scale circulation, and finally, to long-term density-dependent seawater circulation referred to as long-term SGD in this study. The composition of circulating seawater in SGD is often enriched or depleted in many elements relative to conservative mixing with fresh SGD, and may be as significant as rivers to ocean budgets. Multiple assessments and data compilation have been conducted to analyze the impact of fresh SGD and nutrient fluxes. These investigations represent a critical advancement towards comprehending the significance of coastal aquifers in influencing ocean chemistry. Nevertheless, due to the intricate nature
Table 1: Water fluxes to the ocean associated with SGD compared to rivers.

<table>
<thead>
<tr>
<th>Source / Mechanism</th>
<th>Flux $(10^3 \text{ km}^3/\text{y})$</th>
<th>Estimated residence time in the aquifer</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivers</td>
<td>35-43</td>
<td></td>
<td>30, 31</td>
</tr>
<tr>
<td>Fresh (terrestrial) SGD</td>
<td>0.2-0.8</td>
<td></td>
<td>27, 28</td>
</tr>
<tr>
<td>Subtidal pump (mechanism #5 in Fig. 2)</td>
<td>96</td>
<td>Hours to days</td>
<td>19, 18</td>
</tr>
<tr>
<td>Long-term SGD (mechanism #1 in Fig. 2)</td>
<td>1-4</td>
<td>Years to hundreds of years</td>
<td>Estimated here</td>
</tr>
<tr>
<td>Intertidal pump (mechanism #2 in Fig. 2)</td>
<td>1.2</td>
<td>Hours to days</td>
<td>19, 18</td>
</tr>
<tr>
<td>Total SGD</td>
<td>120</td>
<td></td>
<td>32, 18</td>
</tr>
</tbody>
</table>

![Fig. 2: Seawater circulation mechanisms in coastal aquifers.](image)

- **years to thousands of years**
- **hours-days**
- **months**
- **minutes to hours**

of groundwater flow and the range of time-scales that affect groundwater composition differently, there is still ambiguity regarding the elemental budgets influenced by circulating seawater.

**Long-term SGD chemistry: key to solute fluxes in the ocean**

The key to resolving SGD fluxes into the ocean lies in distinguishing and understanding the distinct mechanisms and their respective influences. In this section, we establish the idea that major elements
are influenced only by long-term SGD (process #1 in Fig. 2). Additionally, we highlight the significant difference in time scale between density-driven circulation and other circulation mechanisms, with the former operating at least an order of magnitude longer (Table 1, Fig. 2). This understanding is based on our knowledge of groundwater flow mechanisms in coastal aquifers and consistent field observations from previous studies. It is important to note that geothermal convection (mechanism #6 in Fig. 2) is a long-term process occurring offshore along the continental shelf. Unlike the density-driven flow, it does not involve mixing with fresh water, and there is limited supporting data available. However, its fluxes may be combined with the density-driven flow at this point.

The physical process of density-driven (dispersive) seawater circulation (long-term SGD) in coastal aquifers drives saltwater from the sea into the land below the fresh-saline transition zone, where it mixes with fresh water near the toe, and then flows back into the sea in the mixing zone. There is no mixing between young circulating seawater and fresh groundwater, and thus the saltwater component in the fresh-saline transition zone reflects the long-term circulating SGD component.

Thus, there are two distinct timescales of seawater circulation in coastal aquifers. The major elements are primarily influenced by the long-term process of seawater circulation, as reflected in the groundwater composition in offshore wells (Supplementary Information, Tables S1, S2). On the other hand, groundwater sampled from the shoreline in subterranean estuaries, which mostly represent short-term circulation mechanisms and water-rock interaction, is affected only by conservative mixing with fresh groundwater and does not exhibit the behavior observed in offshore wells.

The key takeaway here is the presence of two distinct time scales of seawater circulation in coastal aquifers, where the major elements are exclusively influenced by the long-term process. The impact on major elements becomes evident only after several years. Our compilation of major elements in coastal aquifers has showed that the predominant process is interpreted as cation exchange (Supplementary Information, Table S1), resulting in enrichment of Ca\(^{2+}\) and Sr\(^{2+}\) and depletion of K\(^{+}\) and Na\(^{+}\) in the circulated groundwater compared to seawater. In addition, a recent study has indicated that the significance of cation exchange, resulting in Ca\(^{2+}\) enrichment and Na\(^{+}\) and K\(^{+}\) depletion, is negligible over the course of several years. This is supported by the observation that most samples in the younger groundwater, align with a conservative mixing trend between the fresh and saltwater end members.

Characterizing long-term SGD end-member composition

We compiled available data from typical coastal aquifers that exhibit an enrichment in Ca\(^{2+}\), Sr\(^{2+}\), and Mg\(^{2+}\), and a depletion in Na\(^{+}\) and K\(^{+}\) (~90% of all studies), in order to assess the end-member composition of the major elements in long-term SGD. The enrichment or depletion in each groundwater sample was determined by comparing it to a conservative mixing model (methods section and Supplementary Information, Table S1).
In cases of ion exchange, the enrichment of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ is counterbalanced by the depletion of $\text{Na}^{+}$ and $\text{K}^{+}$, resulting in a relationship of $(\Delta\text{Ca}^{2+} + \Delta\text{Mg}^{2+}) = -(\Delta\text{Na}^{+} + \Delta\text{K}^{+})$, as depicted in Fig. 3. It is worth noting that due to the high concentration of $\text{Na}^{+}$ in seawater, the $\Delta\text{Na}^{+}$ values often have large uncertainties, typically falling within the analytical error of $\text{Na}^{+}$ concentration.

While ion exchange is the most commonly cited explanation for this behavior, other mechanisms such as reverse weathering and clay formation may also contribute. Fig. 3 suggests that deviations from the (-1) slope line may be attributed to these additional processes. Research has shown that hydrolysis of feldspar and dissolution of carbonate minerals can release $\text{Ca}^{2+}$ into the water, while reverse weathering and clay formation can remove $\text{K}^{+}$, $\text{Mg}^{2+}$, and $\text{Na}^{+}$. The removal ratio of $\text{K}:\text{Na}:\text{Mg}$ due to reverse weathering is typically 0.96:0.39:0.05, respectively. Experiments involving various clay minerals and seawater indicate that, in most cases, water loses $\text{Na}^{+}$ and $\text{K}^{+}$, gains $\text{Ca}^{2+}$, and may either lose or gain $\text{Mg}^{2+}$ depending on the clay mineral present. The amount of $\text{Na}^{+}$ removed in coastal aquifers’ groundwater (Supplementary Information, Table S2) is generally an order of magnitude greater than the amount of $\text{K}^{+}$ removed (in equivalents). Fig. 3 also illustrates that it is uncommon for $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ to be lost while $\text{Na}^{+}$ and $\text{K}^{+}$ are gained, suggesting that the simultaneous addition or loss of all four cations is more common, indicating weathering and precipitation of minerals.

Assessing long-term SGD and solute fluxes

In this section, we calculate the long-term SGD flux by considering the budgets of $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, $\text{Na}^{+}$, $\text{K}^{+}$, $\text{Sr}^{2+}$, $87\text{Sr}/86\text{Sr}$, and $\delta^{26}\text{Mg}$. Our data indicate that the average flux of $\text{Mg}^{2+}$ through long-term SGD is negligible. However, considering the decrease in the heavy magnesium isotope in subterranean estuaries, it remains a significant contributor to the low $\delta^{26}\text{Mg}$ content in the ocean.

To account for uncertainties, we constrain the long-term SGD water flux based on all element and isotope budgets together, as shown in the Extended Data, Fig. 6. This allows us to recalculate the solute and isotope budget to the ocean, enabling a reassessment of the sources and sinks of the different elements and isotopes. We first assume steady-state conditions and then discuss transient conditions.

Under steady-state conditions, the long-term SGD water flux ($Q_{LT} \text{[L}^3/\text{T}]$) can be calculated from the global elemental ocean budget:

\[ \Sigma F_i + F_{LT} = 0 \]  \hspace{1cm} (1)

and

\[ F_{LT} = Q_{LT} \cdot C_{en} \]  \hspace{1cm} (2)
Fig. 3: A global compilation of major elements enrichment and depletion in coastal aquifers’ groundwaters. The enrichment/depletion is calculated as the addition/deficit of a particular element compared to its expected concentration due to conservative mixing only. The shaded area reflect enrichment in the divalent cations and depletion in the monovalent cations. Data, end-members for each site, references and calculations are in the methods section and Supplementary Information, Table S2. Since the enrichment/depletion in $\text{Mg}^{2+}$ is not noticeable in most cases but two$^{47,48}$ and includes large uncertainties (Supplementary Information, Table S1), the y axis reflects only the enrichment in $\text{Ca}^{2+}$ for the rest of the studies. Data with uncertainties above 70% were filtered out from this data set.

where $F_i \ [\text{M/L}^3]$ represents the element flux or removal associated with process $i$, $F_{\text{LTC}} \ [\text{M/L}^3]$ denotes the element flux or removal through long-term SGD, and $C_{\text{en}} \ [\text{M/L}^3]$ is the enrichment or depletion of the element due to long-term SGD. Therefore, the long-term SGD flux can be calculated as follows:

$$Q_{\text{LTC}} = -\Sigma F_i / C_{\text{en}}$$

In the same manner, the long-term water flux can be calculated from an isotope budget in steady state given:

$$\Sigma F_i [R_i - R_{\text{sw}}] + F_{\text{LTC}}[R_{\text{LTC}} - R_{\text{sw}}] = 0$$

thus,
\[ Q_{LT C} = - \frac{F_i[R_i - R_{sw}]}{C_c[R_{LT C} - R_{sw}]} \] (5)

where \( R_i \) and \( R_{sw} \) are the isotope ratios of source \( i \) and seawater, respectively, \( C_c[M/L^3] \) is the concentration of the elements in the long-term SGD component, and \( R_{LT C} \) is the isotope ratio in the long-term SGD groundwater. \( F_i \) includes all fluxes of the sources and sinks except the long-term SGD flux (Table 2).

We calculated the distributions of the long-term SGD flux (\( F_{LT C} \)) using a multi-element Monte Carlo simulation. Normal distributions were assigned to all parameters listed in Table 2. The enrichment and depletion distributions of groundwater end-members in coastal aquifers were estimated using the expectation-maximization algorithm. The number of distributions was determined based on the best coefficient of determination (\( r^2 \)). The distributions were fitted by assigning each value to the distribution with the highest probability and calculating the mean and standard deviations over multiple iterations. Further details on the parameter distributions and goodness of fit can be found in the methods section and Extended Data Figs. 1 and 2. The calculated long-term SGD flux is \( 1998 \pm 810 \text{ km}^3/\text{y} \).

The utilization of multi-element and isotope systems, especially when considering the combination of elements that undergo removal and addition through the same process, plays a crucial role in effectively constraining the long-term SGD flux.\(^{30}\) This enables a more accurate determination of the solute fluxes. Furthermore, the distinct contribution or removal of different major elements ratios by each of these processes (Fig. 1) enables the differentiation between the various processes that impact the budgets in the ocean. The calculated long-term SGD flux and the corresponding solute fluxes are summarized in the extended data, Fig. 6 and Table 2.

The calculations performed above assume steady-state conditions, which means that the sources and sinks presented in this model (Table 2) reflect the average input and output over the residence time scale of each element. Precipitation of minerals, sedimentary processes, seafloor weathering, and the estimates of long-term SGD end members are all influenced by water-rock interactions, occurring on time scales significantly shorter (less than 100 years) than geological time-scales. However, hydrothermal fluxes at mid-ocean ridges and river fluxes can vary over glacial-interglacial time scales, while the estimated fluxes reflect the average over these time scales. The current fluxes can be the result of an increase in element flux due to enhanced weathering,\(^{68}\) a decrease in element flux due to reduced weathering,\(^{33}\) or changes in the hydrothermal input.

We conducted tests on seven distinct scenarios, varying the hydrothermal and river fluxes at 0.5-fold or 1.5-fold the current steady-state fluxes. In addition, we examined a scenario where both hydrothermal and river fluxes were 1.5-fold the current flux, and an additional scenario with a carbonate precipitation of 0.565-fold (Extended Data, Figs. 6, 7, and Supplementary Information ST2). The results indicate that if the river fluxes are overestimated,\(^{68}\) it will lead to higher estimates of the long-term SGD flux.
Table 2: Summary of elements' sources and sinks in the ocean.

<table>
<thead>
<tr>
<th>Element</th>
<th>Source</th>
<th>Flux (Tmol/y)</th>
<th>Residence (Ma)</th>
<th>Output fluxes (Tmol/y)</th>
<th>Long-term SGD flux (km³/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca²⁺</td>
<td>Rivers</td>
<td>13 ± 1.32</td>
<td>3.23 ± 0.73</td>
<td>8.3 ± 0.83</td>
<td>1.9 ± 0.19</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>Hydrothermal</td>
<td>1.3 ± 0.5</td>
<td>-1.6 ± 0.59</td>
<td>0.25 ± 0.025</td>
<td>0.85 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Subduction zones</td>
<td>-0.1 ± 0.005</td>
<td>-0.43 ± 0.043</td>
<td>0.02 ± 0.005</td>
<td>1.3 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Mineral precipitation</td>
<td>-32 ± 4.8</td>
<td>-2.0 ± 0.2</td>
<td>-0.4 ± 0.043</td>
<td>-120 ± 35</td>
</tr>
</tbody>
</table>

References and comments:
- Ca, Mg, Na, K, Sr isotopes.40, 51, 53, 52
- Mag interconnects are based on the composition of clay minerals in 59
- Interaction with sediments: Ca, Mg, Na, K, Mg isotopes fractionation are estimated from altered basalts in subduction zones.60
- Ca, Mg fluxes are relevant only to the isotope budget. Ca is assumed to remain constant during the alteration of continental crust in high and low temperatures; thus, fluxes are relevant only to the isotope budget. Ca is removed during circulation, almost no data on Na see ST1, Sr 51, 53, 52

Summary of elements' sources and sinks in the ocean, along with the corresponding end-member concentrations used in the model. The table also presents the model output of solute and water fluxes under steady-state conditions (SS), as well as a scenario considering higher hydrothermal and river fluxes (R1.5H1.5). Uncertainties are given as ±1σ.
based on Ca\(^{2+}\), Mg\(^{2+}\), and Sr\(^{2+}\) budgets, while the estimates for K\(^{+}\), Na\(^{+}\) and \(^{87}\text{Sr}/^{86}\text{Sr}\) will be lower (Extended Data, Fig. 7 and Supplementary Information ST2). The most consistent results are observed for the steady-state and higher hydrothermal and river flux scenarios, which represent an underestimate of the current fluxes. The latter scenario (R1.5H1.5) yields water and solute fluxes that are 65% of the steady-state scenario but are also comparable to river fluxes (Table 2).

**Consistency between sediment accumulation and element enrichment:** In order to ensure a consistent enrichment of a specific element over geological timescales, it is essential to accumulate a sufficient amount of solid material that can continuously supply this element at a rate comparable to its addition to the ocean. To estimate this accumulation, we performed a rough calculation using reasonable parameters: a coastal aquifer with a cross section of 10 km in length and 100 m in depth, a deposition rate of 1 mm/year, a sediment calcium (Ca) concentration of approximately 4 moles/kg, a density of 2600 kg/m\(^3\), and a total shore length of \(1.5 \cdot 10^5\) km. Based on these values, we estimate an annual calcium accumulation of approximately 16 Tmol, which is of the same order of magnitude as the calculated flux.

However, it is challenging to account for the observed calcium fluxes into the ocean solely through ion exchange, which typically occurs on clay minerals and oxide surfaces. This suggests the involvement of other water-rock interaction processes, such as clay formation and weathering, to support the observed fluxes.

**The effect of long-term SGD on the ocean carbon budget**

The water and solute fluxes from coastal aquifers to the ocean are influenced by sea level changes in transient conditions, which can play a role in moderating the transition between warmer and colder climates on glacial-interglacial time scales. Sea level changes impact the magnitude of water and solute fluxes\(^3,69\) with fluxes increasing during sea level drop and decreasing during sea level rise. This means that during colder periods when sea level is dropping, there would be a higher addition of Ca\(^{2+}\) at the expense of Na\(^{+}\) and K\(^{+}\), while the opposite would occur during warm periods.

Reducing the Ca\(^{2+}\) flux by half to 16 Tmol/y during sea level rise over 10 thousand years will decrease the Ca\(^{2+}\) concentration in the ocean by 0.1 mM (assuming Ca\(^{2+}\) removal follows a first-order reaction). A straightforward analysis of the carbon system and the precipitation/preservation of CaCO\(_3\) in the ocean suggests that this reduction would lead to a decrease in atmospheric CO\(_2\) levels of approximately 10 ppm (Supplementary Information ST4), thereby mitigating the overall trend of rising atmospheric CO\(_2\). However, in the scenario of cooling over 90 thousand years and doubling the flux from coastal aquifers (or increasing the flux by 10% over 100 million years), there would be an increase of approximately 60 ppm in atmospheric CO\(_2\), slowing the overall pattern of declining atmospheric CO\(_2\). This suggests that coastal aquifers have the potential to influence CO\(_2\) levels during cooling periods, thereby moderating the cooling effect, and vice versa during warming periods.
On short time scales, the changes in major element fluxes are unlikely to have a significant impact on their concentrations in the ocean due to their long residence times. However, it is crucial to understand the dynamics between sea level changes, coastal aquifer fluxes, and other relevant processes (as depicted in Fig. 1) on glacial-interglacial and geological time scales. This understanding is essential for unraveling the complex relationship between the ocean, carbon cycle, and climate, as well as identifying potential feedback mechanisms.

Summary and conclusions

The various processes controlling major elements in the ocean involve different ratios of element addition and removal. Hydrothermal circulation contributes to the removal of Mg$^{2+}$ and the addition of K$^+$ and Ca$^{2+}$. Lower temperature seafloor weathering removes Mg$^{2+}$, K$^+$, and Na$^+$, while the formation of clay minerals (reverse weathering) removes these three elements but adds Ca$^{2+}$ (Fig. 1). Long-term SGD, influenced by water-rock interactions and the mixing of fresh water, demonstrates a pronounced terrestrial influence on aquifer water and sediments. As a result, it leads to the removal of Na$^+$ and K$^+$ and the addition of Ca$^{2+}$, while showing minimal change in Mg$^{2+}$.

The diverse range of reactions observed in these different processes provides valuable insights for constraining the sources and sinks of major elements in the ocean, particularly the contribution from long-term SGD.

We have successfully quantified the water and solute fluxes from coastal aquifers into the ocean, shedding light on the carbon budget, which was previously only discussed qualitatively. Our calculations reveal that the significance of coastal aquifers in shaping the chemical composition of the ocean and influencing isotope fluxes cannot be overlooked any longer.

Methods

Characterizing SGD end-members

For each study (field site), we calculated the enrichment or depletion of all major elements (Ca$^{2+}$, Mg$^{2+}$, Na$^+$, K$^+$, and Sr$^{2+}$). These calculations were based on the reported composition of fresh groundwater and seawater in the respective studies, or the seawater composition provided in Table 2. The enrichment or depletion factors were determined by assuming that chloride behaves conservatively, using the following equation:

$$C_{en} = C_s - C_{fw} - \frac{Cl_s - Cl_{fw}}{Cl_{sw} - Cl_{fw}} \cdot (C_{sw} - C_{fw})$$

where $C_{en}$ is the enrichment or depletion, $C$ in the concentration of a given element, Cl in the chloride
concentration, and subscripts $s$, $sw$, and $fw$ refer to sample, seawater, and freshwater, respectively. All concentrations are in [M/L$^3$].

All calculations and end-members used are summarized in the Supplementary Information, Table S2; errors were calculated by propagating an analytical error of 5% on the major elements concentrations. The enrichment and depletion distributions of the elements were utilized to determine the end-member of the long-term SGD flux in the model. To account for uncertainties, the errors in the enrichment and depletion values were considered by assuming a normal distribution. Subsequently, normal distributions or multiple normal distributions were fitted to each element using the expectation-maximization algorithm. The number of normal distributions was determined based on the optimal coefficient of determination ($r^2$) obtained from the linear fit between the observed and predicted probabilities.

The data set was filtered by selecting chloride concentrations higher than 10% of seawater. In cases where the reaction occurred before complete mixing with freshwater, the enrichment values were corrected based on the dilution factor. Further details regarding the distribution fitting process and the correction for dilution can be found in the Extended Data, Figs. 1 and 2.

$^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{26}\text{Mg}$: The end member values for $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{26}\text{Mg}$ were determined based on existing datasets. For $^{87}\text{Sr}/^{86}\text{Sr}$, the brackish and long-term SGD components were distinguished using data published by Beck et al. The brackish flux data was considered representative of short-term SGD influenced by tides and waves, with minimal impact on strontium concentration but noticeable effects on its isotope composition. The dataset was divided into short-term and long-term SGD, and the most abundant value (based on a 10-bin histogram) was selected to represent the composition of the seawater end-member for the short-term (brackish) SGD (after correcting according to the mixing equation). The determination of the long-term SGD end-member involved filtering the dataset based on a Sr enrichment of $> 8 \mu m$ and a salinity of at least 20% of seawater ($n=2$). Data from Yucatan, which could introduce a bias towards carbonate aquifers, was excluded from the analysis. The strontium flux of the short-term SGD was calculated using a water flux of 550 km$^3$/y. For $\delta^{26}\text{Mg}$, the end-member value was obtained from Mayfield et al. after filtering the dataset to include only samples with at least 10% seawater salinity.

**Input fluxes used in the model**

All input values for the processes influencing ocean chemistry (Fig. 1) are listed in Table 2 and summarized in the Extended Data, Figs. 3 and 4. The long-term SGD fluxes depicted in these figures represent the additional fluxes required to balance the budget in a steady-state condition. To calculate the water fluxes, we divided these fluxes by the corresponding end-members presented in Fig. 1 and examined the overlap among the solutions in the Monte-Carlo model (Extended Data, Fig. 6).
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Supplementary Information is available for this paper

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References


Supplementary Files

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