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LETTERS

Catastrophic flood of the Mediterranean after the Messinian salinity crisis

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The Mediterranean Sea became disconnected from the world's oceans and mostly desiccated by evaporation about 5.6 million years ago during the Messinian salinity crisis[1–3]. The Atlantic waters found a way through the present Gibraltar Strait and rapidly refilled the Mediterranean 5.33 million years ago in an event known as the Zanclean flood[4]. The nature, abruptness and evolution of this flood remain poorly constrained[4–6]. Borehole and seismic data show incisions over 250 m deep on both sides of the Gibraltar Strait that have previously been attributed to fluvial erosion during the desiccation[4,7]. Here we show the continuity of this 200-km-long channel across the strait and explain its morphology as the result of erosion by the flooding waters, adopting an incision model validated in mountain rivers. This model in turn allows us to estimate the duration of the flood. Although the available data are limited, our findings suggest that the feedback between water flow and incision in the early stages of flooding imply discharges of about $10^8\,m^3\,s^{-1}$ (three orders of magnitude larger than the present Amazon River) and incision rates above 0.4 m per day. Although the flood started at low water discharges that may have lasted for up to several thousand years, our results suggest that 90 per cent of the water was transferred in a short period ranging from a few months to two years. This extremely abrupt flood may have involved peak rates of sea level rise in the Mediterranean of more than ten metres per day.

The main evidence for a kilometre-scale sea level drop in the Mediterranean is the excavation of canyons by the rivers flowing to the empty sea during the Messinian stage, up to 2,500 m deep in the Nile Delta[8] and about 1,000 m deep at the mouth of the Rhone[9]. The salt accumulation in the deeper parts of the basin and the deposition of cyclic alternations between brackish and fresh-water sediment of the Lago Mare facies, combined with high-resolution biostratigraphy and astronomically-calibrated magnetostratigraphy[2,3], indicate that total disconnection between both sides of the Betic–Rifean orogen started about 5.6 million years ago.

The Messinian salinity crisis finished 5.33 million years ago[3], when the Atlantic waters found a way through the present Gibraltar Strait and refilled the Mediterranean in an event known as the Zanclean or post-Messinian flood[4]. There is agreement that this was triggered primarily by tectonic subsidence at the Gibraltar sill, probably related to the sinking of a lithospheric slab under the Betic–Rifean orogen[10], and perhaps in combination with sill erosion[11] and sea-level rise. Outburst floods triggered by overspilling of large lakes have induced dramatic changes in surface hydrology and topography in regions as diverse as the Pleistocene Lake Bonneville[12], the Tertiary Ebro basin[13] (northeast Iberia), or the English Channel[14], but the case of the post-Messinian flood is special because of the enormous size of both the source and the sink basins. The equilibrium level of the isolated Mediterranean during desiccation was between 1,500 m and 2,700 m below present sea level[6,15], implying that the flooding water volume was three orders of magnitude larger than that at Lake Bonneville. Because they were based on an arbitrary evolution for the depth of the Gibraltar Strait during the flood, previous estimates of the flood duration yielded divergent values ranging between ten years[4] and a few thousand years[5,6]. To quantify and understand the abruptness of the post-Messinian flood we needed to incorporate the dynamics of rock incision as the mechanism that progressively excavated the floodway and let ever increasing flow of Atlantic waters into the Mediterranean basin.

The present maximum depth of the Gibraltar Strait ranges between 284 m at the present Camarinal sill (the shallowest pass between the Atlantic and the Mediterranean; Fig. 1) and about 900 m at the Strait itself. Its present morphology might be affected

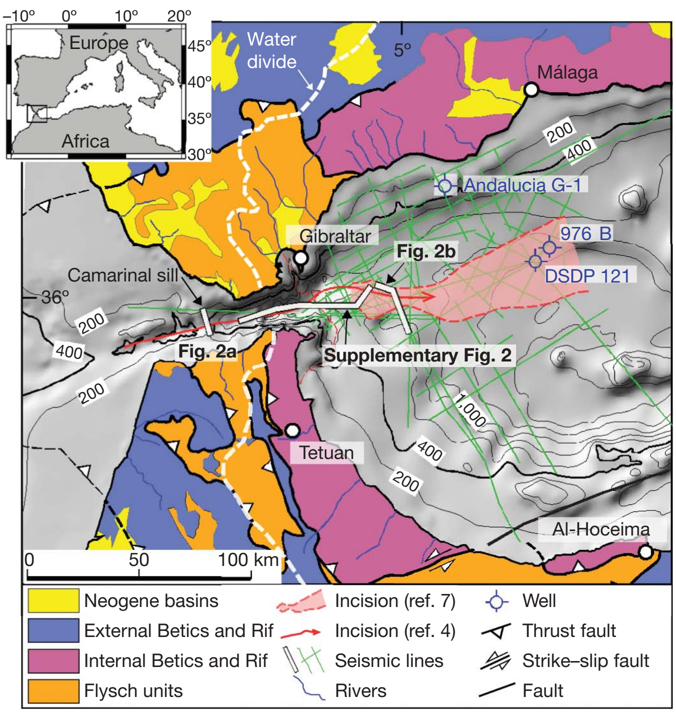

Figure 1 | Geological map and bathymetry of the Gibraltar Arc region. The extent of the erosion channel is shown (after refs 4 and 7). The incision channel cuts 70 km beyond the drainage divide, which we interpret as the result of westwards retrogressive erosion during the post-Messinian flood. The interpretation of the seismic lines is correlated with the three located wells. Fault tectonic deformation has been minor since the Messinian. The water divide between the Atlantic and Mediterranean rivers is shown as a white dashed line.

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by the strong streams between both oceanic domains and by tectonic vertical motions after flooding, rather than being an intact relict of Messinian or Zanclean incision. However, the streams did not impede deposition in the strait after the Messinian (Fig. 2a and Supplementary Fig. 2), and therefore they cannot be responsible for the bulk of the present bathymetry. As for tectonic motions, if present at all after the Messinian, they are limited to long-wavelength isostatic or dynamic motions such as those controlling the onset[16] and the end[10] of the Mediterranean isolation, because local fault deformation is minor[11,17] (see, for example, Fig. 2b).

The strongest evidence for a deep incision channel across the Gibraltar Strait comes from recent boreholes and from seismic data. Drilling cores related to the Africa–Europe tunnel project (Fig. 2a) show a thickness of at least 250 m of flysch breccia redeposited or slumped into a trough carved across the original flysch units (Late Cretaceous to Neogene in age) outcropping in the Iberian and Moroccan sides of the strait[18,19]. A similar eastward-oriented incision is observed further to the east, in the Alboran side of the strait[7] (Fig. 1). Both features have previously been interpreted as subaerial (fluvial) erosion during the Messinian desiccation[4,11,18]. In Fig. 2b and Supplementary Fig. 2 we present two sample seismic profiles correlated with Ocean Drilling Program (ODP) site 976 and the commercial well Andalucia G-1[20,21] through a large set of other publicly available seismic surveys (Fig. 1). These profiles provide evidence for the geometry of this incision and its continuity across the Gibraltar Strait along at least 200 km. As previously recognized[18], this erosive channel is incised into Miocene deposits and filled by Pliocene–Quaternary sediments, and merges laterally with the basin-wide Messinian Erosional Surface (MES). In areas unaffected by the widespread

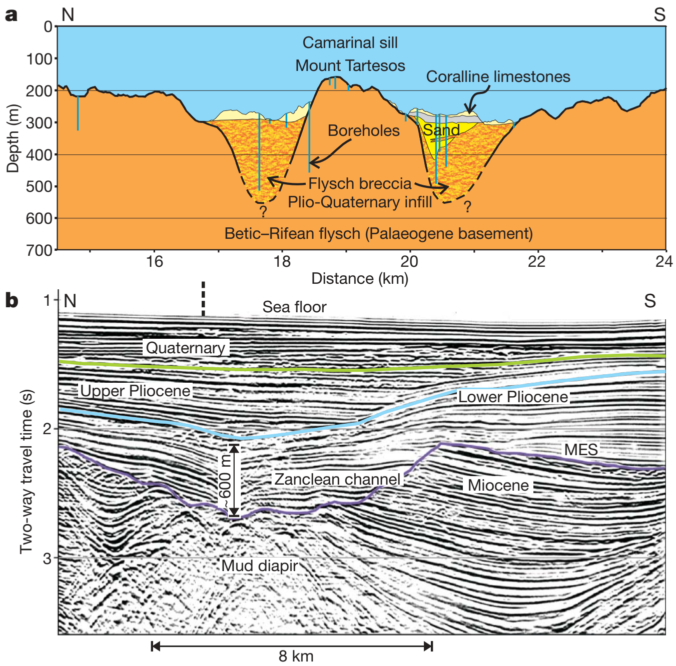

Figure 2 | Evidence for an erosion channel across the Gibraltar Strait. **a**, Section across the Gibraltar Strait based on borehole exploration[18]. Flysch breccia coming from the Betic–Rifean flysch units fill an erosive trough more than 250 m deep. Whether Mount Tartesos is an autochthonous relict of the resistant flysch[18], or a block slumped from the undermined banks of the flooding channel[4] is not clear. Vertical exaggeration is 5:1. **b**, Multichannel seismic profile of Conrad 828 (refs 29, 30) interpreted in this work, based on correlation with the wells located in Fig. 1. The profile shows the dimensions and U-shape of the late-Messinian incision channel in the eastern side of the Gibraltar Strait related to the Zanclean flood. The asymmetry of the channel is partly due to the obliquity of the profile in its northern end (see location in Fig. 1), and partly due to differential isostatic subsidence after the flood[10]. MES, Messinian Erosional Surface. Approximate vertical exaggeration is 4:1.

mud diapirism, the geometry of the incision has a U-shaped cross section with a size varying from 650 m depth by 11 km width near the strait to less than 300 m depth per 6 km in different branches of the channel further to the east. The size of this channel is not comparable to any other Messinian palaeovalley observed in the Alboran Sea, but only to canyons carved during the Messinian desiccation by the largest rivers in the Mediterranean[8,9]. However, the U-shape of this incision (Fig. 2b) and its presence at both the eastern and western sides of the drainage divide (Fig. 1) cast doubt on its formation by subaerial fluvial erosion (typically producing V-shaped valleys) by an eastward-flowing river. Such mechanism would require a large catchment area during the Messinian, but the scarcity of tectonic deformation since that age[11,17] suggests that the drainage divide shown in Fig. 1 has not undergone major changes. Recently, U-shaped erosion channels found in the English Channel have been attributed to a megaflood sourced in a large glacial lake in the North Sea[14].

We therefore postulate that the erosion channel observed in Gibraltar (Fig. 1) was excavated by the Zanclean flood. To validate this hypothesis, we calculate the timing of water flow and incision produced during the overspill of the Atlantic basin into the Mediterranean basin by combining a model of rock incision by water with hydrodynamic equations (see Methods). To calculate the flood evolution displayed in Fig. 3, we searched for combinations of the erosional parameters k_b and a that fit a final sill incision of 240 m (a mean value of observed incision in the eastern and western sides of the strait, averaged across the channel). All model runs show a long first period of very little incision owing to the reduced amount of water discharge allowed by the shallow sill depth of 1 m prescribed at the initial time ($t = 0$). As the Gibraltar gate is excavated growing deeper and wider, water flow and incision rate increase exponentially. This situation persists until water flow becomes limited by the rising level of the Western Mediterranean. This event is labelled as stage 1 in Fig. 3. Later, the reduction of the hydrological gradient between the Atlantic Ocean and the western Mediterranean results in reduction of flow velocity, water discharge and incision rate. As the Sicily sill is reached (stage 2), the level of the western basin (and the hydrological gradient) remains constant and the flooding water discharge is transferred to the eastern basin until this is also filled up to that level (stage 3). Afterwards, the whole Mediterranean rises synchronously while the level difference between basins, the water discharge, and the velocity decrease gradually to zero (stage 4).

For comparison, the three model evolutions in Fig. 3 are shown using a time relative to the instant when the western basin reaches the Sicily sill (t_2, stage 2), which roughly coincides with the time when the rate of sea level rise becomes maximum. Though the exponent of the erosional law a strongly influences t_2 (Supplementary Table 1 and Supplementary Fig. 3), the abruptness of the flood remains relatively insensitive to a. This is shown by defining the bulk duration of the flood Δt_b as the time taken by 90% of the total water transfer. High-a, low-k_b model runs imply slow incision at the first stages and therefore a long period of water supply and basin level rise before the catastrophic flow (large t_2). A priori, this could result in a significant refill of the Mediterranean and a reduction in hydraulic gradient, diminishing the abruptness of discharge, but the results show that this occurs only for unrealistic values of the exponent $a > 3$. Within a values derived for river incision studies, Δt_b changes only from 510 days to 790 days. A complete model parameterization is available in Supplementary Fig. 3.

The amount of incision expected during the post-Messinian flood on the basis of river incision studies (see note 2 in Supplementary Table 1) is comparable in depth and width to the erosion channel observed at the Gibraltar Strait. Using this geometry as a model constraint implies that the Zanclean flood was a catastrophic event (Fig. 3), more abrupt than previously thought[4–6], and involved maximum rates of Mediterranean level rise of over 10 m per day. This abruptness has significance not only for its potential effects on ecosystems of the Mediterranean region but also for its palaeoclimatic

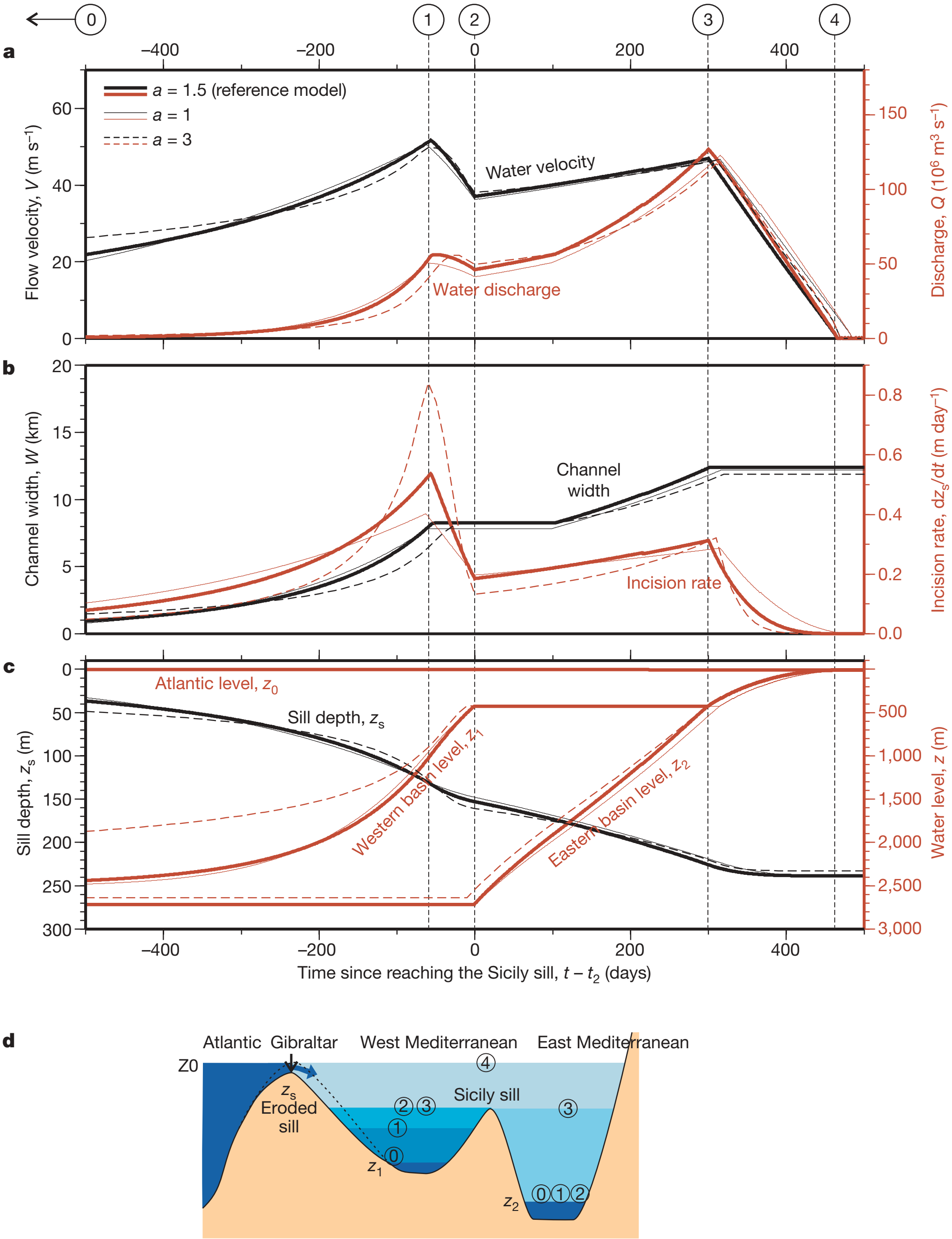

Figure 3 | Evolution of three floods producing a final incision of 240 m, calculated for different exponents of the erosion law *a*. **a**, Water velocity and water discharge through the Gibraltar Strait; **b**, Channel width and incision rate; **c**, Sill depth (black lines) and level of the Atlantic, the Western Mediterranean, and Eastern Mediterranean (red lines). For comparison purposes, time is relative to the time when the Sicily Sill is reached t_2 (Supplementary Table 1). The three floods start with a sill depth of 1 m. Although peak discharges take much longer to arrive for large *a* values, the bulk of the water flow is concentrated in a similar amount of time. Circled numbers refer to the five stages shown in the cartoon **d**: (0) initial time; (1) time of maximum incision rate; (2) western Mediterranean level reaches the Sicily Sill (t_2); (3) eastern basin level reaches the Sicily Sill; and (4) The Mediterranean becomes full.

effects, because a smaller (by two orders of magnitude) outburst flooding at Lake Agassiz has been related to a global cold period around 12,000 years ago[22]. The peak discharge across the Gibraltar Strait reached more than $10^8\,m^3\,s^{-1}$ at a speed of over $40\,m\,s^{-1}$, only months before flood completion, and produced maximum incision rates exceeding 0.4 m per day. For comparison, the Amazon mean discharge is only $1.5 \times 10^5\,m^3\,s^{-1}$ and the Lake Missoula late glacial catastrophic flood has been estimated in $10^7\,m^3\,s^{-1}$ (ref. 23). The Messinian flood implied a dissipation of gravitational potential energy of about 1.6×10^{22} J, similar to the heat transport along the Gulf Stream in a year, and ~4% of the kinetic energy of the K-T Chicxulub meteorite impact[24].

These estimates are consistent with the exceptionally rapid restoration of deep marine conditions recorded at the Messinian–Pliocene boundary[25]. High-resolution sedimentological studies of this boundary[26,27] show a brief freshwater influence on the mineralogy, fauna and stable-isotope composition of carbonates over only 15 cm of sediment in ODP site 975. These might reflect the initial flooding period of relatively slow water flow predicted in our calculations, before stage 1. The flood evolution obtained for high values of the incision law exponent ($a = 3$) undergoes little sea level rise in the Mediterranean for the first few thousand years before the catastrophic flow is triggered. Future studies should determine the spatial distribution of the approximately $500\,km^3$ of rock eroded at the Gibraltar Strait during the flood climax.

We do not envisage the flood as a waterfall, as is often represented: instead, the geophysical data (Supplementary Fig. 2) suggests a huge ramp, several km wide, descending from the Atlantic to the dry Mediterranean with a slope of 1% to 4%, similar to the slope of the present sea floor eastward from Gibraltar. Erosional retreat caused by the flood shifted the sill 30–80 km westwards from its Messinian location at the Gibraltar Strait and shaped the incision channel and the bulk of the strait morphology as we see them today.

METHODS SUMMARY

To use the incision around the Gibraltar Strait as a constraint for the flood velocity, we developed a one-dimensional model that accounts for the feedback between water-flow-controlled incision and sill-depth-controlled water flow. The formulation, based on previous river incision studies[28] and on hydrodynamic formulae, is detailed in the Methods. In essence, the model is based on the approach that incision rate dz_s/dt underneath a water flow is a power-law function of basal shear stress τ_b:

$$\frac{dz_s}{dt} = k_b(\tau_b)^a \quad (1)$$

where k_b and a are positive constants. An analytical solution of this equation coupled to slope-driven water flow shows that sill incision grows exponentially with time in the early stages of flooding, the speed of this incision being dependent on the lithological erodibility k_b and the effective slope on the Mediterranean side of the sill. For the post-Messinian flood, erosion rate doubles in timescales of ten to a hundred years, showing that feedback between incision and water flow is a key control of the timing of the flood.

The interplay between incision (as the floodgate opener) and slope reduction due to the replenishment of the Mediterranean is calculated using an explicit finite-difference time-iterative technique, starting with an initial sill depth of $z_s = 1$ m at $t = 0$. At each time step, water discharge is calculated based on the depth of the sill and then sill incision is calculated based on basal shear stress and effective slope S (hydrological gradient). As the Mediterranean becomes filled, S gradually decreases to zero. The calculated water discharge is passed from the Atlantic Ocean to the western Mediterranean basin and, if the Sicily sill (430 metres below sea level) is reached, to the eastern Mediterranean basin, accounting for a reconstructed hypsogram of the Messinian Mediterranean (after ref. 6).

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions D.G.-C. planned the study, performed the modelling and wrote the paper; F.E. and C.G. managed and interpreted the seismic lines; I.J.-M. helped with interpretation and writing; M.F. helped in study design; J.V. and R.D.V. took care of the tectonic aspects. All authors discussed the results.

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METHODS

Consider a sill at an average depth $z_s > 0$ (a positive value of depth means below initial ocean level) acting as a water gate between a source basin (the Atlantic Ocean) at level z_0 and a sink basin (the western Mediterranean basin) at level z_1 ($z_1 > z_s > z_0$). Symbols are depicted in Supplementary Fig. 1. The incision rate dz_s/dt under a water flow is generally approached as a power-law function of basal shear stress τ_b (equation (1)). The unit stream power approach, including water velocity V as multiplying factor of τ_b in equation (1), has also been tested, but the predicted floods are more abrupt than those shown here because incision is more concentrated at the fastest flooding stages. River incision studies show that a ranges between 1 and 3 (ref. 28). For $a = 1$, k_b ranges between 10^{-5} and 2×10^{-4} m yr^{-1} Pa^{-1} (ref. 31) and $\sim 10^{-7}$ m yr^{-1} Pa^{-1} (ref. 32) for river bed incision, and is 18–40 m yr^{-1} Pa^{-1} for unconsolidated soil erosion[33]. For $a = 1.5$, k_b has been estimated at 8×10^{-6} m yr^{-1} Pa$^{-1.5}$ (ref. 34).

Shear stress at the sill can be approached as the product of water density ρ, the acceleration of gravity g, the mean water depth of the channel $(z_s - z_0)$ and the slope of the water surface S (also known as hydraulic gradient):

$$\tau_b = \rho g (z_s - z_0) S \tag{2}$$

We assume that $S = H/L$, where $H = z_1 - z_0$ is the head loss, and length $L = 100$ km, which maximizes the half-width of the Betic–Rifean orogen. For a conservative estimation of S we impose a limit of $H < 1{,}000$ m (representative for the present depth of the Alboran Sea). We note that adopting higher slopes would result in a more abrupt flood.

To calculate the water flow over the sill and the level of the Mediterranean basins, we use an empirical relationship relating water flow speed V with the hydraulic gradient S (Manning's formula), frequently used to estimate outburst flood discharges[14]:

$$V = \frac{1}{n} R_h^{\frac{2}{3}} S^{\frac{1}{2}} \tag{3}$$

where V is the average velocity (in metres per second), $n = 0.05$ is the roughness coefficient, and R_h is the hydraulic radius (in metres) of the strait connecting the Atlantic and the Mediterranean. The hydraulic radius is a measure of the flow efficiency of a river channel, and because channel width is significantly larger than channel depth, it can be estimated as $R_h \approx z_s - z_0$. River discharge (in cubic metres per second) can be calculated as $Q = W(z_s - z_0)V$, where the W is the width of the channel expressed in metres. At each iteration we update the value of W using a relationship derived from river channel studies[35]:

$$W = k_w Q^{a_w} \tag{4}$$

where $a_w = 0.5$ is an empirically determined constant (see, for example, refs 34 and 35) and $k_w = 1.2$ is a value comparable to normal rivers that has been calibrated here to account for the final width of the Gibraltar Strait, assuming this coincides with the present strait width $W = 14$ km. The model predictions have a very small sensitivity to these parameters, as well as to the assumed initial width.

It is possible to solve the feedback dynamics analytically taking z_0 and S as constant (which is valid as long as head loss is not reduced by the refill of the Mediterranean):

$$\frac{dz_s(t)}{dt} = K(z_s - z_0)^a \tag{5}$$

where $K = k_b(\rho g S)^a$ for $K > 0$. The solution to equation (5) for $a = 1$ for the sill depth as a function of time is:

$$z_s(t) = z_s(0) + ce^{Kt} \tag{6}$$

Therefore the sill is incised exponentially with time in the early stages of water flow, and the speed of this growth is dependent mostly on the lithological erodibility k_b and the slope in the Mediterranean side S. For the post-Messinian flood, $K = 10^{-2}$ to 10^{-1} per year, indicating that erosion rate doubles in timescales of ten to a hundred years and that the feedback between incision and water flow is relevant to the timescales of the post-Messinian flood.

To study a more general scenario incorporating both the role of incision (as the mechanism excavating the water gate) and the head-loss reduction due to the replenishment of the Mediterranean, we numerically solved equations (1) to (4) using an explicit finite-difference time-iterative technique. A time step of 0.1 days is used, starting with an initial sill depth of $z_s = 1$ m below the initial ocean level, taken as $z_0 = 0$. We note that changing the initial sill depth from 1 m to 0.1 m induces a strong delay in the reference flood (t_2 increases from 14 to 47 years; see note 4 in Supplementary Table 1), while the predicted maximum flooding rates undergo otherwise insignificant changes (the flood evolution is just shifted in time). Our model cannot determine whether this initial sill depth is related to tectonic subsidence at the Gibraltar Strait[10], or to global sea level rise, or to erosion of the sill[11]. For the Mediterranean basins we adopt initial levels of $z_1 = 2{,}500$ m (west) and $z_2 = 2{,}700$ m (east) below sea level[36]. The predicted timing of the flood does not vary substantially for a more conservative initial level of 1,500 m. Global sea level drops 9.5 m as a result of the flood, although this result uses the present global ocean hypsometry as a proxy for the one at Messinian times.

The initial geometry adopted for the flooding channel is conservative in the sense that it is chosen to find a maximum estimate for the duration of the flood. For this reason, we have adopted a low value for both the initial slope ($S = 1\%$) and a mean incision (240 m for the examples in Fig. 3). Similarly, we have neglected other mechanisms that may have increased incision during the flood, such as cavitation[12]. It is also implicitly assumed that the observed incision is due to a single flood. If an earlier flood took place, its incision across the sill should have been raised above sea level to close the Mediterranean and, in order to affect our estimation of the amount of incision, should be brought below sea level again before the next flood occurred. In other words, multiple flooding could only induce an overestimation of the amount of incision in the presence of post-flood uplift and desiccation-related subsidence at the sill. These vertical sill motions are exactly the opposite of those predicted for the Messinian choking of the Mediterranean[10]. It is therefore unlikely that the incision resulted from multiple flooding. Supplementary Fig. 3a shows the effect of the estimated total incision on the predicted duration of the flood.

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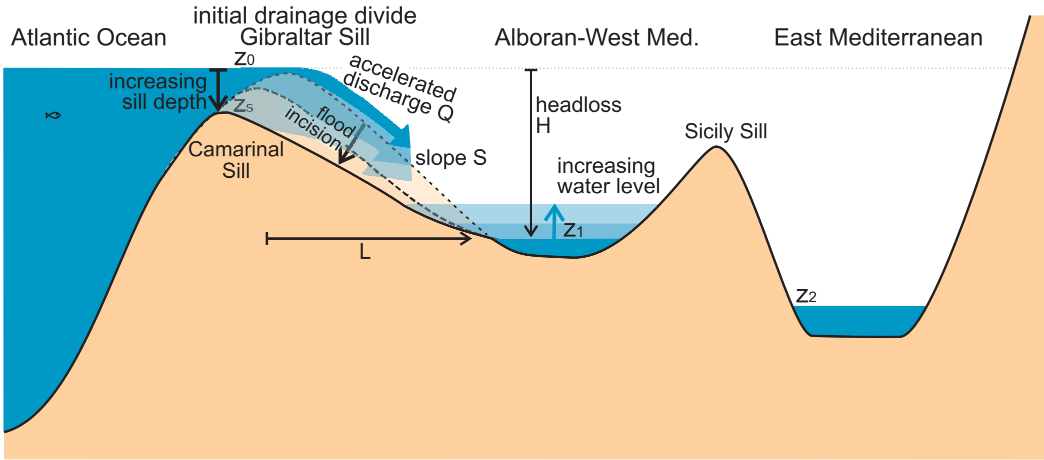

Figure SI-1.- Conceptual model of feedback between water-flow shear stress and sill incision at the Gibraltar Strait. Notation is defined in the *Methods*. Incision at the sill is controlled by rock erodibility and water flow, which is calculated as a function of sill depth z_s-z_0 and head loss H. In turn, the increasing sill depth implies an exponential growth of water discharge that ends only as head loss H is reduced. The progress of the flood is determined by the total amount of incision, which allows constraining the erodibility parameters. The volumes adopted for the western and eastern Mediterranean are based on reconstructions by Meijer & Krijsgsman[6]. Evaporation and precipitation are not significant at the time scales of the flood.

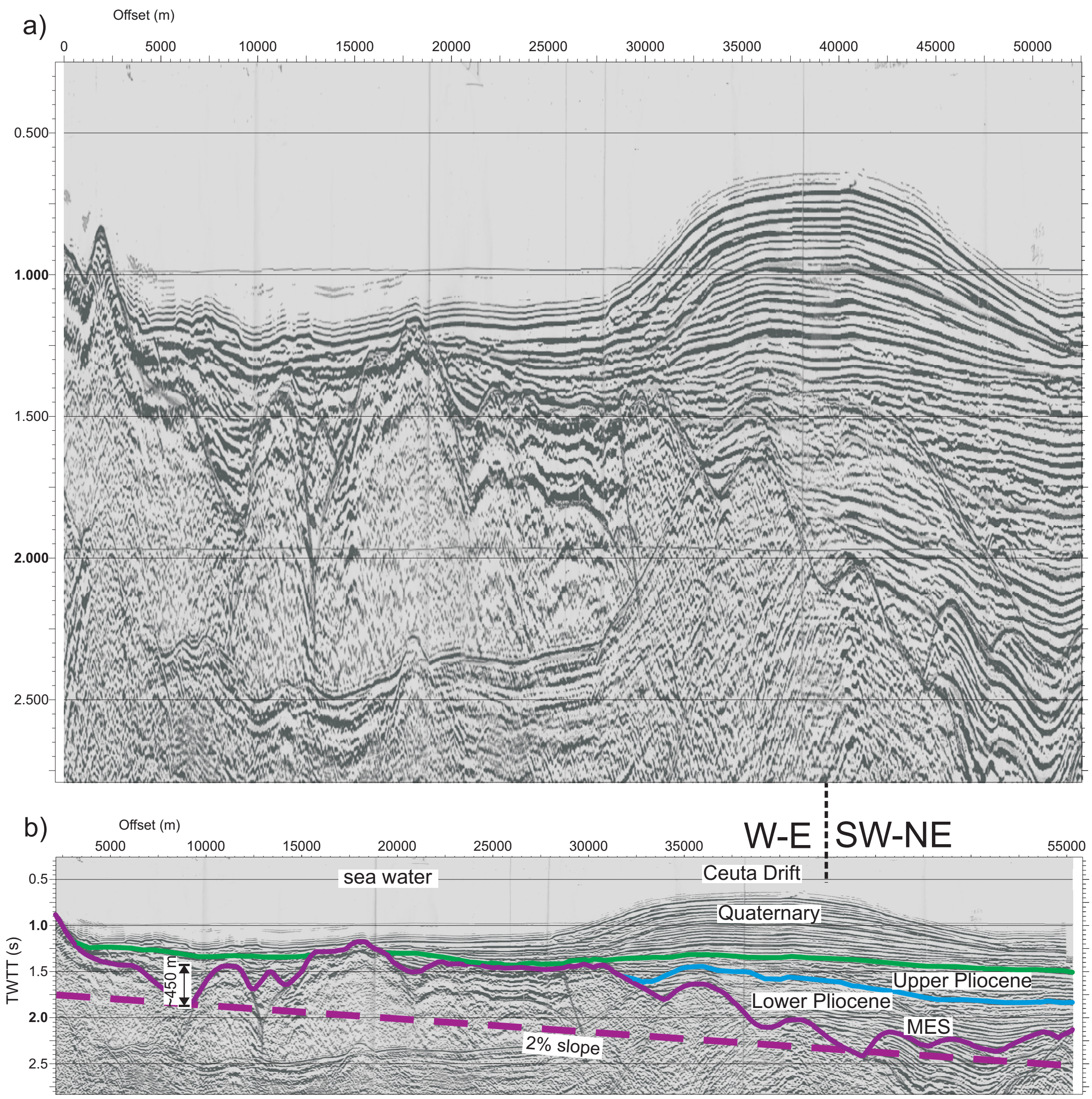

Figure SI-2. Multichannel seismic profile Conrad 829 along the Gibraltar Strait. a) Row data; b) Interpretation based on correlation with the wells located in Fig. 1. Approximate vertical exaggeration is 15:1 (a) and 5:1 (b). The vertical axis is two-way travel time of the seismic waves. The profile follows the channel path only roughly, and the offset between both induces the undulations in the MES reflector (Messinian Erosional Surface). Taking the deepest points of the western and eastern sides as indicators of the channel axis depth yields a channel slope of ca. 2%. Location in Fig. 1. The sedimentary mound is a contourite depositional system (Ceuta Drift) resulting from the interaction of the Mediterranean outflow water and sediments coming from the Moroccan margin. Most seismic lines located in Fig. 1 are available at the websites of the Instituto Geológico y Minero de España (IGME) and the Institut de Ciències del Mar (ICM-Barcelona).

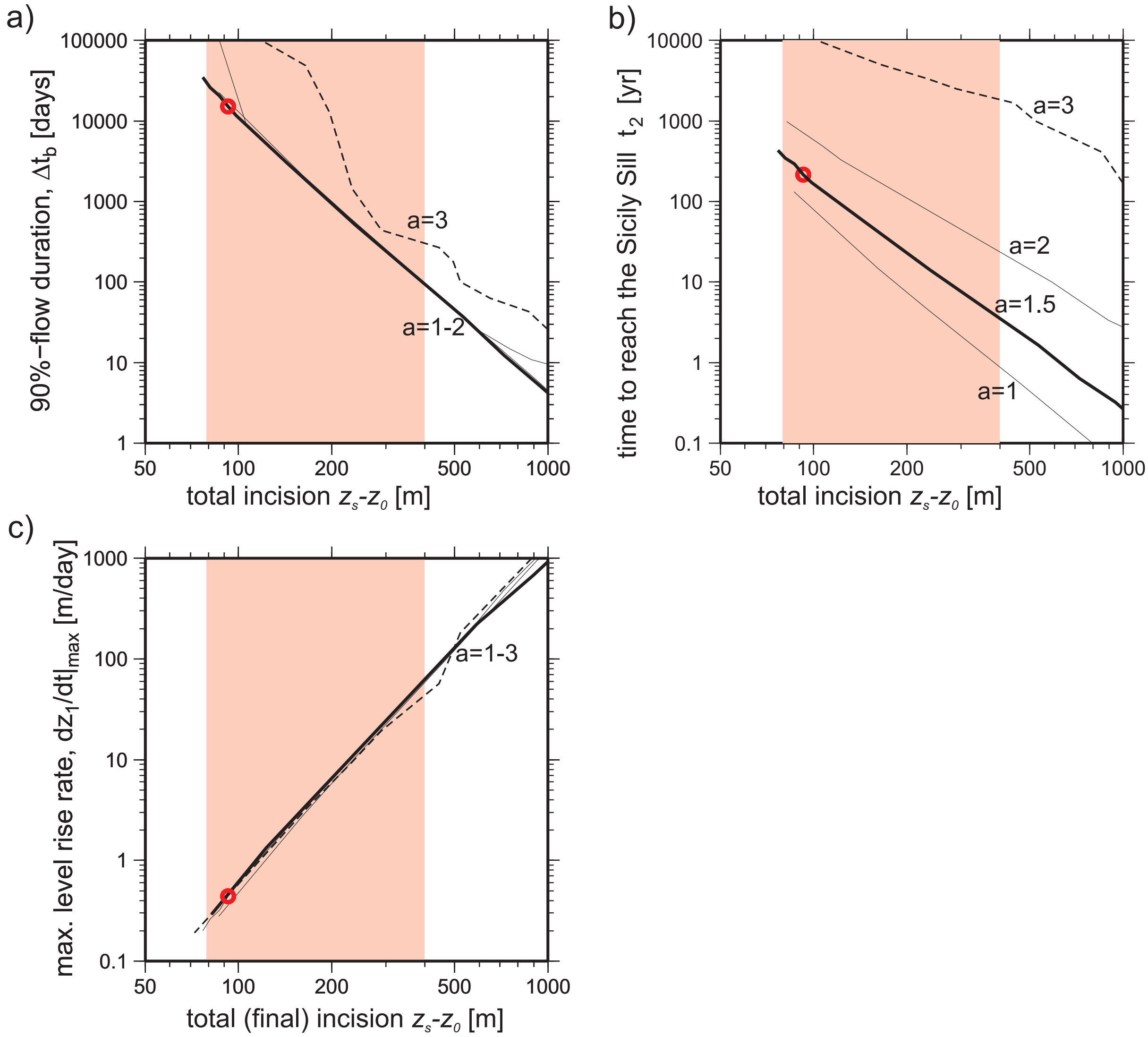

Figure SI-3. Model parameterization. Relationship between the calculated total sill erosion z_s-z_0 and: a) the time lapse taken by 90% of the water flow Δt_b; b) the time when sea level reaches the Sicily Sill t_2; and c) the maximum level rise rate dz_1/dt. The values predicted for river incision parameters from Attal et al.[34] are indicated with a circle. The shaded area indicates the range of incision observed, averaged across the sill in the Gibraltar area.

Table 1. Results for selected combinations of input parameters *a*, k_b. The reference model is indicated in bold.

Shear stress power law exponent *a*	Shear stress law constant k_b [m yr^{-1} Pa^{-a}]	Total incision z_s-z_0 [m]	Max. water level rise rate, dz_1/dt_{max} [m/day]	Time elapsed to reach the Sicily Sill , t_2 [years]	Max. water discharge [10^6 m^3 s^{-1}]	90% water flow completion time, Δt_b [days]
1	(1) $1.15 \cdot 10^{-2}$	240	10.71	4.2	123	510
1.5	**(1) $1.30 \cdot 10^{-4}$**	**240**	**11.84**	**14.0**	**127**	**514**
3	(1) $1.63 \cdot 10^{-10}$	240	10.91	3,072.0	128	790
(2) 1.5	(2) $8.00 \cdot 10^{-6}$	92	0.44	215.6	4.3	15100
(3) 1.5	(3) $1.30 \cdot 10^{-4}$	271	35.82	5.3	390	168
(4) 1.5	(4) $1.30 \cdot 10^{-4}$	240	11.83	47.1	127	514

(1)Erosion parameter values imposed to obtain a 240 m total incision; (2)Parameter values derived from river incision by Attal et al.[34]; (3)Same erosion parameters as in the reference model but adopting double initial slope (*L*=50 km); (4)Same erosion parameters as in the reference model but adopting an initial sill depth of z_s=0.1 m instead of 1 m..