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Links between ocean temperature and iceberg discharge during Heinrich events

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Palaeoclimate records have revealed the presence of millennial-scale climate oscillations throughout the last glacial period[1]. Six periods of extreme cooling in the Northern Hemisphere—known as Heinrich events—were marked by an enhanced discharge of icebergs into the North Atlantic Ocean[2,3], increasing the deposition of ice-rafted debris[2]. Increased sliding at the base of ice sheets as a result of basal warming has been proposed to explain the iceberg pulses[4–6], but recent observations[7,8] suggest that iceberg discharge is related to a strong coupling between ice sheets, ice shelves and ocean conditions. Here we use a conceptual numerical model to simulate the effect of ocean temperature on ice-shelf width, as well as the impact of the resultant changes in ice-shelf geometry on ice-stream velocities. Our results demonstrate that ocean temperature oscillations affect the basal melting of the ice shelf and will generate periodic pulses of iceberg discharge in an ice sheet with a fringing shelf. We also find that the irregular occurrence of Heinrich events seen in the palaeoclimate records can be simulated by periodic ocean forcing combined with varying accumulation rates of the ice sheet. Our model simulations support a link between millennial-scale ocean temperature variability and Heinrich events during the last glacial period.

Marine and continental sediments as well as ice-core records reveal the existence of millennial climatic oscillations during the last glacial period, referred to as Heinrich[2] and Dansgaard–Oeschger events[1]. The transitions between cold (stadial) and warm (interstadial) phases of the Dansgaard–Oeschger cycle have been simulated by forcing the ocean circulation with variable freshwater fluxes in models with a bi-stable regime of the thermohaline circulation in the glacial North Atlantic Ocean[9]. However, whether Dansgaard–Oeschger events are related to the internal ocean variability or to an external forcing is still an open debate[10]. 'Heinrich events' are defined by pulses of ice-rafted debris (IRD) in North Atlantic sediments. Six major pulses have been identified during the period 70–14 kyr BP. The materials composing the lithic layers have largely a Canadian[11], but also European and Icelandic origin[12]. The transport of IRD across the Atlantic to lower latitudes, even down to the Portugal coast, can be explained only by enhanced discharge of icebergs and their subsequent melting[1,3]. The considerable sea surface cooling during these events has been associated with a collapse of the thermohaline circulation[13]. All six Heinrich events occurred within a stadial state at the end of Bond cycles, which have been defined as long-term cooling cycles including several progressively colder Dansgaard–Oeschger events[14]. These features suggest that Heinrich events consist of catastrophic discharges of icebergs from Northern Hemisphere ice sheets linked or triggered by some oceanic process. However, the triggering mechanism and its relationship with climate variability remains a very important unsolved problem of Quaternary climatology.

Table 1 | The behaviour of the model is dependent on some chosen parameter values.

Parameter	Value	Unit
Acc	0.25 (0.001–1)	m yr^{-1}
k_d	2.5 (1–10) $\times 10^{-10}$	m^{-1} yr^{-1}
k_{stream}	5 (1–10)	m yr^{-1}
β_0	4.5 (1–10)	m yr^{-1}
k_L	10^3	None
L_c	320 (150–450)	km
H_2^{Calv}	380 (150–450)	m
k_{Calv}	7.5 (0.125–12.5) $\times 10^{-3}$	yr^{-1}
k_{Bm}	0.575	m yr^{-1}
Bm_0	0.25	m yr^{-1}
τ	1,500 (1,500–6,000)	yr

The left numbers in the second column represent the values used in the standard simulation. The ranges of values given in parentheses are those used for various sensitivity tests. The dependence on the accumulation is discussed in the main text. The magnitude of the major iceberg discharge depends on the ice stream velocities (k_{stream}) and of the minor calving episode depends on the elevation threshold (H_2^{Calv}), but do not have significant consequences on the oscillatory behaviour depicted in the standard simulation. The dependence on the other parameters, their physical relevance and their link with the real world are systematically discussed in Supplementary Information.

A common explanation of Heinrich events consists of a switch of the basal thermal conditions of the Laurentide ice sheet leading to periodical purges of continental ice through the Hudson Strait into the North Atlantic Ocean[4–6]. However, three-dimensional thermomechanical ice-sheet models are unable to satisfactorily reproduce the binge–purge mechanism without adding an *ad hoc* basal sliding parameterization[5,6,15]. Such parameterizations lead to high horizontal ice velocity gradients clearly inconsistent with the shallow-ice approximation on which these models are based. It has also been shown that the amplitude and the periodicity of the resulting simulated instabilities are strongly model dependent[16]. Moreover, the binge–purge mechanism cannot explain the semi-synchronous deposition of IRD coming from all the Northern Hemisphere ice sheets[3,11,12].

As an alternative to the binge–purge mechanism, it has been proposed that a catastrophic ice-shelf break-up might be the

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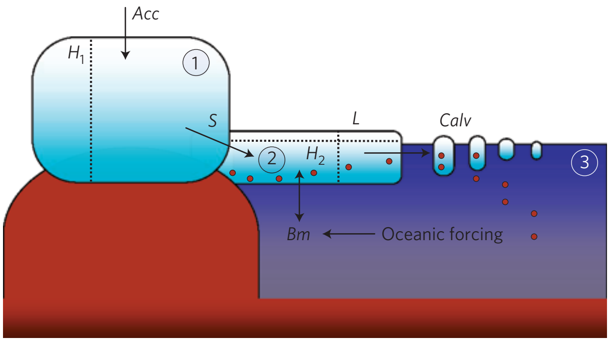

Figure 1 | Schematic of the conceptual model. 1, Grounded ice-sheet; 2, floating part of the ice sheet (ice shelf) and 3, forced ocean. *Acc*, H_1, *S*, H_2, *L*, *Calv* and *Bm* respectively represent the snow accumulation, the grounded ice thickness, the ice flow at the grounding line, the thickness of the embayed ice shelf, the ice-shelf length, the iceberg calving and the basal melting under the ice shelf.

source of iceberg calving associated with Heinrich events[17]. It was postulated that the eastern Canadian ice shelves attained their maximum extent during extreme cold conditions, and that they would have suddenly disintegrated during a climate amelioration. However, this hypothesis does not resolve the fundamental question of the origin of abrupt climate changes that accompanied Heinrich events. On the other hand, several studies based on proxies[18,19] or on model results[20], show subsurface oceanic warming when the Atlantic meridional overturning circulation is reduced. This offers a plausible mechanism to destabilize an ice shelf and suggests that the ocean variability is not only a consequence of Heinrich events, as often assumed, but should also be considered as a potential trigger process. In this respect, the recent break-up of a few ice shelves around the Antarctic Peninsula helps us to better understand the feedbacks between grounded and floating ice. It has been shown[7,21] that glaciers accelerated abruptly just after the disintegration of the Larsen-B ice shelf. This illustrates the importance of the ice-shelf buttressing effect to inhibit the surge of coastal grounded ice streams. All these aspects, probably implicated in Heinrich events, have often been separately studied but never gathered. Here we consider that they should be revisited in a common framework. The original approach of our study is to build a scenario involving all of the main components (grounded ice-sheets, ice-shelves and ocean) to demonstrate that a conceptual model can produce physically based oscillations with frequencies consistent with observational data.

Using the parameter values listed in Table 1, our conceptual model (Fig. 1) has been integrated for 200 kyr (see the Methods section for the model description) to obtain the oscillations shown in Fig. 2 (20–50 kyr). Let us consider that each of these oscillations starts just after a major calving episode. At this time the ice shelf is particularly extended because of gains in mass from an increase of

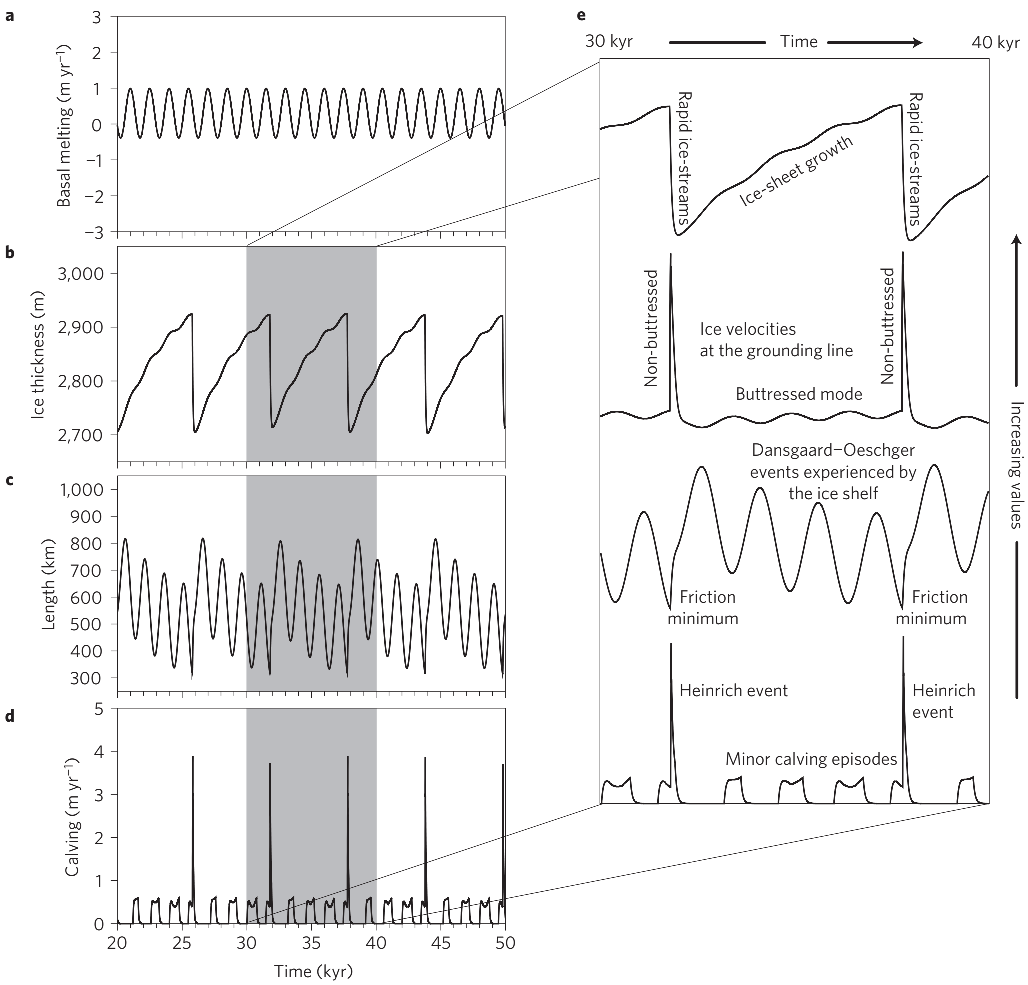

Figure 2 | Standard simulation. a–d, Time evolution of the oceanic forcing (**a**) (in terms of basal melting under the ice shelf), grounded ice thickness (**b**), ice-shelf length (**c**) and iceberg calving (**d**). **e**, The evolution of the same variables as well as the ice velocities at the grounding line over a simulated Bond cycle.

ice advection from the grounded part and a reduced basal melting rate. Subsequently, each prescribed oceanic cycle with resultant variations in basal melting leads to an oscillation of the ice-shelf length with a decreasing trend (Fig. 2a). When the shelf becomes thinner than the elevation threshold, a minor calving episode is produced (Fig. 2c). However, during the first four oceanic cycles the response of the grounded ice sheet is smoothed (Fig. 2b), because the buttressing effect of the ice shelves remains efficient enough to inhibit a drastic ice acceleration at the grounding line. Therefore, the grounded ice sheet continues to grow. Then, a new increase of the basal melting reduces again the ice-shelf thickness. Eventually, the ice shelf shrinks to a threshold extent, allowing the shift to the non-buttressed mode. This leads to an acceleration of the ice flow at the grounded line and triggers a rapid surge of the grounded ice and a massive iceberg discharge (that is, a Heinrich event) (Fig. 2d). This phenomenon occurs with a periodicity (6 kyr) appearing as a multiple of the oceanic forcing period ($\tau = 1.5$ kyr). The succession of the simulated events reproduces a Bond cycle, characterized by ice-shelf lengthening following the oceanic variability and a Heinrich event occurring with a longer periodicity (Fig. 2e). This cycle requires the presence of an ice shelf to produce a resonance of the coupled system with a periodicity four times greater than the imposed oceanic forcing period.

If the system is forced only by a constant basal melting rate, our model rapidly tends to the equilibrium and does not show any oscillation even for drastically changed initial conditions (see Supplementary Information, Section S2). Therefore, our model needs to be excited through the ocean to fall into an oscillatory equilibrium. To test the dependence of this mechanism on the oceanic forcing signal, another set of experiments has been carried out, in which different noises are added to the oceanic forcing. In the case of an oceanic forcing with only high-amplitude noise (that is, four times greater than that of the standard basal melting), the model oscillates in a multi-frequency mode (see Supplementary Information, Section S3). However, when a periodic signal with weaker amplitude is superimposed on this noise, the model recovers a similar periodic behaviour as in the standard simulation. The most probable duration between two consecutive Heinrich events is still ~6 kyr (4τ, as in the standard simulation), but other periodicities arise: ~7.5 kyr (5τ), ~4.5 kyr (3τ), ~9 kyr (6τ) and ~3 kyr (2τ). The oscillatory behaviour is not dependent on the forcing, supporting the robustness of the mechanism we propose here.

The choice of $\tau = 1.5$ kyr in the standard simulation is justified by the fact that this period has been implicated in the occurrence of Dansgaard–Oeschger events[22]. Nevertheless, we also tested the model dependence on different but less significant oceanic forcing periods that are also present in the Dansgaard–Oeschger cycle ($\tau = 3$, 4.5 and 6 kyr; ref. 22). In these cases, the model still produces output periodicities that are multiples of the input periods (see Supplementary Information, Section S4). In light of these results, we can now provide a physical explanation for the Heinrich event occurrence within the context of Bond cycles. To trigger a Heinrich event, two conditions are needed: an ice-shelf break-up and an acceleration of the ice flow at the grounding line triggering a rapid surge of the grounded ice streams. This double requirement is more easily reached at frequencies that are multiples of the oceanic forcing period. This means that the process triggering Heinrich events results from a resonance of the prescribed Dansgaard–Oeschger cycle, and explains why a succession of Dansgaard–Oeschger events is observed in palaeorecords between two consecutive Heinrich events (known as a Bond cycle).

As in the binge–purge-based models[4–6], we find a strong link between the snow-accumulation rate and the oscillations frequency (Fig. 3). For low accumulation values, the model oscillates with large periodicities. Conversely, if accumulation rates are large

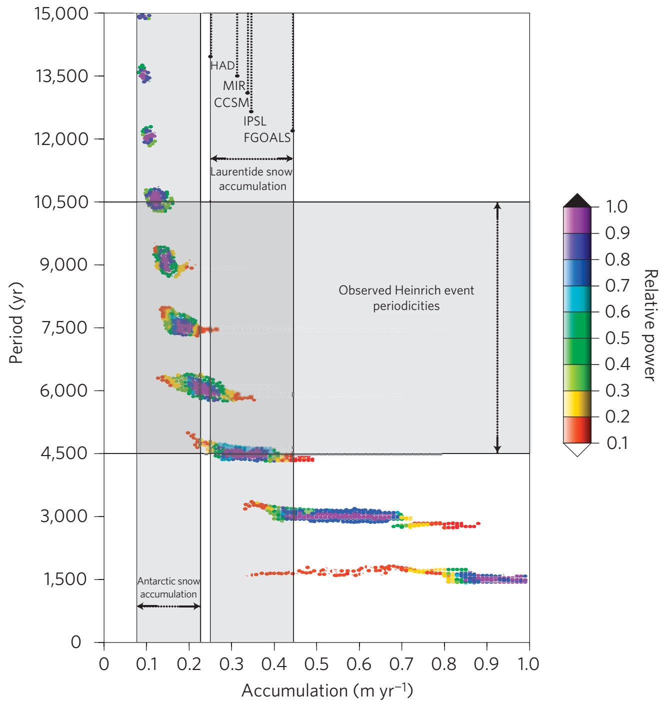

Figure 3 | Spectral analysis of the time-dependent grounded ice thickness. To explore the oscillatory behaviour of the model under different values of the snow-accumulation rate, 1,000 simulations with accumulation ranging between 0.001 and 1 m yr^{-1} have been carried out. The Fourier transform of each of these simulations yields the normalized power of the main components and their periods. A given point in the figure represents the period for a given accumulation and the colour illustrates its relative power. As a comparison (grey shading), the present-day Antarctic snow accumulation is given. The smaller bound corresponds to the East Antarctica value and the upper one corresponds to the western part of the ice sheet[27]. The Laurentide snow accumulation has been calculated from the PMIP-2 runs[28], by an interpolation method[29]. HAD, MIR, CCSM, IPSL and FGOALS are respectively the Hadley Center, Miroc, CCSM, IPSL and FGOALS general circulation models.

enough (~0.9 m yr^{-1}), the grounded ice sheet oscillates in phase with the oceanic forcing. In this case, a major calving episode occurs each 1.5 kyr cycle. This dependence on accumulation is not continuous but discrete, allowing the occurrence of privileged periodicities around τ-multiples and the absence of oscillations for other periods. As the accumulation rate over the northern ice sheets had a considerable variability during marine isotope stage 3, the dependence of our simulated Heinrich events with the accumulation and the irregular occurrence of Dansgaard–Oeschger events observed in data, provide an explanation for the irregular periodicity of Heinrich events observed in marine sediments.

Heinrich events are strictly defined as episodes of IRD deposition on the ocean floor. Therefore, the capture of debris that accompanied ice surges must also be considered. It is generally accepted that debris are captured into the ice when ice basal layers drag the ground over a cold base. An attractive point of the binge–purge mechanism[4–6] is that a cyclic shift between a cold and a melted base implies a periodical debris capture into the ice. Our conceptual model is constructed such that an active ice-stream always flows over a melted base, which seems in contradiction with debris capture. However, at the onset of the ice stream, a cold-base region may be present. As a result of the roughness of the bedrock, the transition between cold and temperate bases is not a line but a transition zone (probably a few kilometres in size), with patches of cold and temperate bases. Debris might be captured in this transition zone. Moreover, when the ice stream is slow, less heat is produced at the base and the transition zone must shift downstream (and upstream again when the ice stream becomes more active). Even if the amplitude of this shift is much smaller than in the thermally driven binge–purge theory, debris could be incorporated by the same process. Finally, the edges of the main and tributary ice-streams are also locations where debris could be captured.

In our approach, we consider only a single oceanic layer. Our simulated Heinrich events occur for high basal-melting values of the prescribed oceanic cycle. It is therefore important to constrain whether a subsurface oceanic warming caused by a reduction of the Atlantic meridional overturning circulation strength is capable of destabilizing an ice shelf. This would provide an explanation for the Heinrich event occurrence during the stadial periods.

These results provide new insights for understanding the mechanism that led to the recorded iceberg discharges during these events and their link with oceanic variability. Future studies based on more sophisticated models that include smaller-scale processes will have to accurately assess the scenario depicted here. In contrast to previously proposed Heinrich event mechanisms, a very important result shown here is that this process can be explicitly related to the presence of Dansgaard–Oeschger events, which is supported by all the available data.

Methods

Model description. Our three-box model (Fig. 1) computes the mass balance of the grounded ice sheet using the difference between accumulation, *Acc*, and ice advection to the ice shelf, *S*. The temporal evolution of the grounded ice thickness, H_1, is defined as:

$$\frac{dH_1}{dt} = Acc - S(t)$$

We consider that ice thickness changes involved in Heinrich events are mainly located over Hudson Bay and Hudson Strait[15] and they are not affected by the strong ablative regime of the Laurentide ice sheet southern edge. Therefore, changes in surface mass balance by ablation in Hudson area are negligible compared with those driven by ice-flow dynamics[23]. Thus, the mass balance results from the difference between accumulation and ice flow through the grounded line.

In the second model box, corresponding to an embayed ice shelf, the mass balance results from the difference between accumulation, ice advection from grounded ice sheet, *S*, and freshwater input to the ocean, *FWF*. The temporal evolution of the floating ice thickness, H_2, is defined by:

$$\frac{dH_2}{dt} = Acc + S(t) - FWF(t)$$

H_2 is assumed to be proportional to the ice-shelf length, *L*:

$$L = k_L H_2$$

The ice advection at the grounding line is computed as:

$$S(t) = k_{\text{stream}} - \beta(t)$$

where k_{stream} is constant, and β is related to the backforce exerted by the fringing ice shelf to the grounded part because of longitudinal stresses between the ice-shelf edges and the bay:

$$\beta(t) = 2k_D H_2(t) L(t) + \beta_0 \quad \text{if} \quad L(t) > L_c \text{ (buttressed mode)}$$

β is assumed to be proportional to the ice-shelf surface that is rubbing the bay ($2 \times H_2 L$), or not existent when the ice-shelf length becomes sufficiently low:

$$\beta(t) = 0 \quad \text{if} \quad L(t) < L_c \text{ (non-buttressed mode)}$$

k_D is a constant and β_0 represents a constant extra term in the backforce that accounts for all other processes than dragging on the sides of the bay.

The assumption of the two differentiated modes of ice flow at the grounded line (buttressed and non-buttressed) as a function of the ice-shelf size is made here by analogy with that recently observed after the break-up of the Larsen-B ice shelf in the Antarctic Peninsula[7] and also by the observed and simulated effects of the ocean on Pine Island glaciers[24]. The freshwater flux released to the ocean, *FWF*, results from the addition of the basal melting under the ice shelf, *Bm*, and the amount of ice lost by iceberg calving, *Calv*:

$$FWF(t) = Bm(t) + Calv(t)$$

where

$$Calv(t) = k_{Calv} H_2(t) \quad \text{if} \quad (H_2(t) < H_2^{Calv} \text{ or non-buttressed mode})$$

or

$$Calv(t) = 0 \text{ otherwise}$$

where k_{Calv} and H_2^{Calv} are constants. We assume that the ice shelf can break when its thickness is small enough or when the ice shelf is not buttressed allowing a large expansion of its length[25]. We consider that over the ice shelf the water resulting from surface melting infiltrates into crevasses and the proportion of this water released to the ocean is negligible. Therefore, the loss of ice results only from basal melting or iceberg calving. Concerning the oceanic variability, we postulate here the existence of a Dansgaard–Oeschger cycle resulting in a periodic variation of high-latitude oceanic temperatures that produce in turn a periodic variation of the basal melting rate:

$$Bm(t) = k_{Bm} \cos\left(\frac{2\pi}{\tau} t\right) + Bm_0$$

where k_{Bm} and Bm_0 are constants and τ represents the imposed Dansgaard–Oeschger cycle period.

Note that k_L represents the constant length-to-thickness ratio of the ice shelf. However, it must also be considered as the aspect ratio of the model. The variables relative to ice fluxes are treated in the model as one-dimensional vertical terms. Therefore, to translate ice velocities at the grounded line (*S*) and calving rate (*Calv*) into three-dimensional expected values (obtained from a three-dimensional ice-sheet model or observed in the real word), these variables have to be multiplied by the aspect ratio k_L.

It is important to note that the set of parameter values given in Table 1 was chosen to compute realistic values of all the model variables. Nevertheless, we did not carry out any specific tuning to fit model results with any palaeo-indicator.

External forcing. There are other plausible mechanisms than basal melting to destabilize an ice shelf that have not been included in these equations. The main one consists of surface melt-water penetration at depth through crevasses, which may lead to the fracture of the ice shelf. This mechanism has been observed and studied in present-day Antarctic ice shelves[26]. It would be unreasonable to say that this mechanism was not present during the last glacial period. Therefore, in the context of our conceptual model, we argue that water infiltration in crevasses most likely occurs during interstadial periods. When surface climate shifts into a stadial phase, the melt-water that is produced at the surface and that infiltrates crevasses is reduced. However, we postulate in this study that during stadial periods, a subsurface warming occurs under the ice shelves, reducing therefore their thickness through an enhanced basal melting. The crevasse depths then represent a stronger ratio of the ice-shelf thickness and thereby favour a major calving rate.

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Author contributions

All authors contributed to the analysis of model results and commented on the manuscript. J.A.-S. and C.R. developed the box model and defined the design of the experiments. J.A-S., S.C. and C.R. participated in the writing of the manuscript. C.D. provided technical support and implemented analytical tools.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to J.A.-S.