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Deeply incised submarine glacial valleys beneath the Greenland ice sheet

M. Morlighem[1*], E. Rignot[1,2], J. Mouginot[1], H. Seroussi[2] and E. Larour[2]

The bed topography beneath the Greenland ice sheet controls the flow of ice and its discharge into the ocean. Outlet glaciers move through a set of narrow valleys whose detailed geometry is poorly known, especially along the southern coasts[1–3]. As a result, the contribution of the Greenland ice sheet and its glaciers to sea-level change in the coming century is uncertain[4]. Here, we combine sparse ice-thickness data derived from airborne radar soundings with satellite-derived high-resolution ice motion data through a mass conservation optimization scheme[5]. We infer ice thickness and bed topography along the entire periphery of the Greenland ice sheet at an unprecedented level of spatial detail and precision. We detect widespread ice-covered valleys that extend significantly deeper below sea level and farther inland than previously thought. Our findings imply that the outlet glaciers of Greenland, and the ice sheet as a whole, are probably more vulnerable to ocean thermal forcing and peripheral thinning than inferred previously from existing numerical ice-sheet models.

Since the 1970s, ice thickness has been measured using airborne radar sounders that detect bed echoes at nadir, that is, directly beneath the path of the radar illumination[6]. Although this approach provides a comprehensive description of ice-sheet thickness in the interior regions[7], the most dynamic sector of the ice sheet—the 211 marine terminating glaciers that control 93% of its ice drainage to the ocean and the overall state of mass balance of the ice sheet[8]—is affected by considerable uncertainties in bed topography and ice thickness. One reason is that the detailed mapping of glacier thickness requires dense radar surveys, which are costly, time consuming and impractical over all the glaciers. Second, the presence of crevasses at the surface, the steep, rough and entrenched character of the glacial valleys and the rugged subglacial topography generate high radar clutter and ambiguous returns that mask bed echoes[9,10]. Third, in the warmer parts of the ice sheet, supraglacial and englacial water inclusions form a highly absorptive medium that limits or even suppresses penetration of radar signals into ice[11]. Fourth, geostatical techniques, for example, kriging[12], that interpolate radar sounding data onto a regular grid are not effective at extrapolating the measurements to areas with no observations. Despite major advances in radar sounding technology in the 1990s and a tripling of radar acquisitions from 2001–2008 to 2009–2013 with Operation IceBridge (OIB; ref. 13), major gaps in glacier thickness remain in all sectors of Greenland—and especially southern Greenland. This places a fundamental limit on the reliability of numerical ice-sheet-flow models, including those that use simplified physics or flowline models constrained by the existing thickness maps[2,3].

Here we combine the sparse, airborne, radar sounding-derived ice thickness data with comprehensive, high-resolution, ice motion derived from satellite interferometric synthetic-aperture radar (InSAR; ref. 8). We employ a mass conservation (MC) algorithm[5] to calculate ice thickness, and bed topography is deduced by subtracting ice thickness from a digital elevation model of the ice surface[14]. The algorithm conserves mass fluxes while minimizing the departure from the original radar-derived ice thickness data[5,15] (Supplementary Information). Ice surface motion provides a physical basis for extrapolating sparse ice thickness data to larger areas with few or no data. The method works best in areas of fast flow, where errors in flow direction are small and the glaciers slide on the bed. In the interior regions, where errors in flow direction are larger, we employ kriging to interpolate ice thickness. The output product is generated at the same spatial scale as the ice motion product—in this case 150 m spacing, or seven times better than a recent kriging compilation[16]. The thickness data product is self consistent with the ice velocity data by design, so numerical models that use these data do not require spin-up procedures to obtain a stable initial state when using these data[17]. Obtaining a similar level of precision and measurement density with radar surveys would be impractical. Conversely, bed topography at a scale of a few hundred metres fulfils a fundamental requirement of numerical models of grounding line dynamics, a foremost aspect of glacier stability and evolution[18].

Our discussion focuses on bed topography, which is not subject to large temporal changes, in sharp contrast with ice thickness, which may change rapidly. Our bed topography provides the first comprehensive view of the entire periphery of Greenland (Fig. 1). Although our compilation is not different from earlier compilations in the interior—for example, the total ice volume is the same—our results differ significantly along the coast. We report the widespread presence of well-eroded, deep bed troughs along the ice-sheet periphery, generally grounded below sea level, coincident in location and spatial extent with fast flow features ($>100\ \mathrm{m\,yr^{-1}}$) and extending over considerable distances inland (100 km). Most of the bed depressions are not apparent in the existing ice thickness records because radar sounders fail to detect bottom echoes on most of these glaciers[7].

The collocation of the bed troughs with areas of fast flow implies that the ice-covered valleys are of glacial origin—that is, generated by long-term (10^4–10^5 yr) glacial erosion of the bed[19]. The bed troughs are indeed 100% U-shaped rather than V-shaped[20] (Supplementary Information). Conversely, the correspondence between subglacial valleys and fast flow indicates that fast-flow features have been geographically stable for a long period of time. The network of sub-glacial valleys carved by glacial cycles forms a

[1]University of California, Irvine, Department of Earth System Science, Croul Hall, Irvine, California 92697-3100, USA, [2]Jet Propulsion Laboratory—California Institute of Technology, 4800 Oak Grove Drive MS 300-323, Pasadena, California 91109-8099, USA. *e-mail: Mathieu.Morlighem@uci.edu

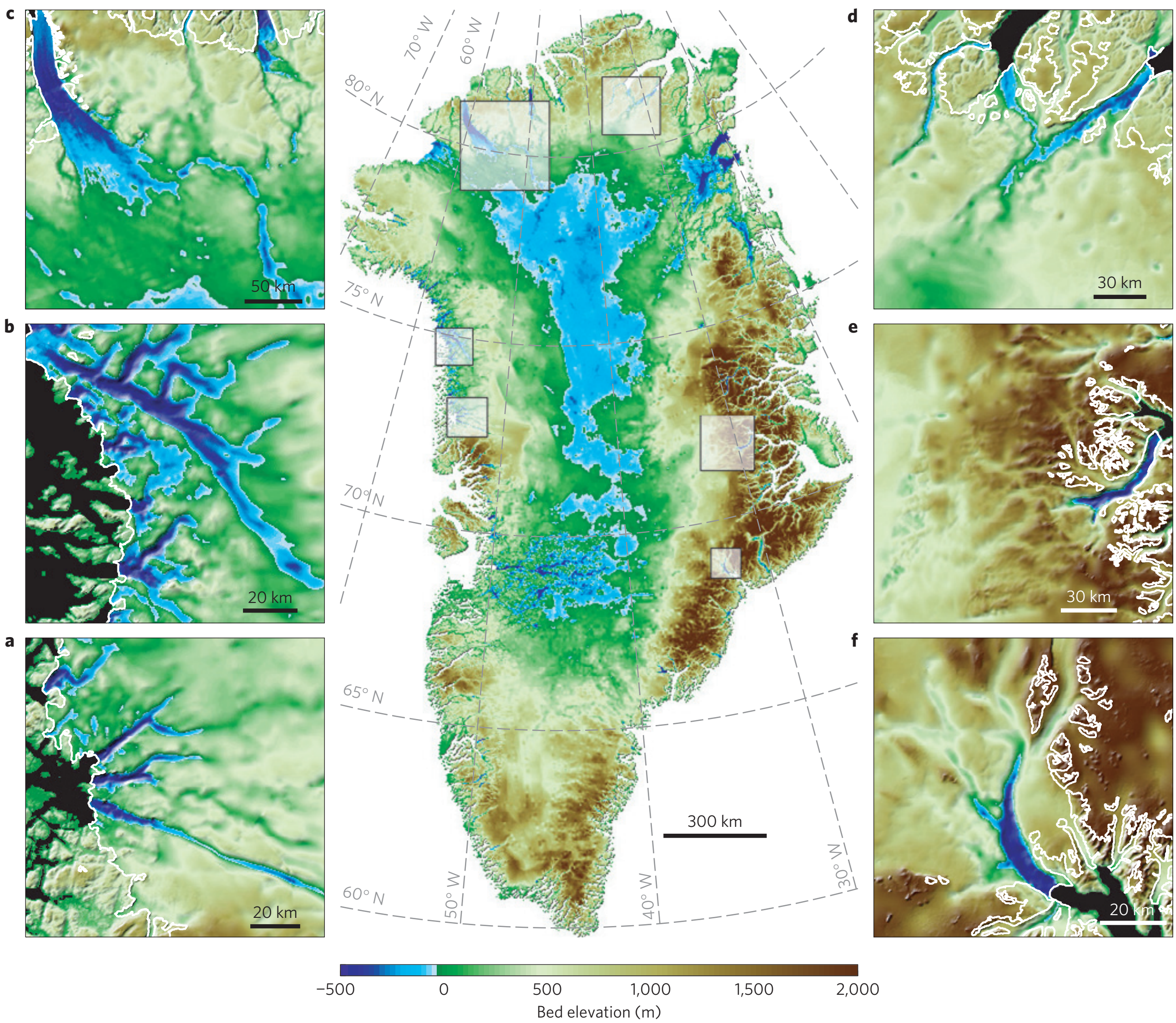

Figure 1 | Bed elevation of the Greenland ice sheet colour-coded between −500 and +2,000 m, with submarine areas in blue. Details of the large-scale map for Upernavik Isstrøm and Nunatakassaap Sermia (**a**), Hayes Gletscher, Allison Gletscher and Illullip Sermia (**b**), Petermann, Steensby and Ryder Gletscher (**c**), Marie Sophie Gletscher, Academy Gletscher and Hagen Bræ (**d**), F. Graae, Charcot and Daugaard-Jensen (**e**), and Kangerlussuaq Gletscher (**f**); glaciers are listed in clockwise order. The white contour line delineates the limit of land ice. The mass conservation method is employed for the glaciers. Kriging is used to map the interior regions.

fundamental geometric constraint on the past, present and future evolution of the ice-sheet flow.

Ice is channelized to the ocean through a narrow set of flux gates along the periphery. Only 8% of the total length of these flux gates corresponds to ice grounded below sea level, yet this small fraction controls 88% of the total ice discharge of Greenland. The subglacial troughs extend tens to hundreds of kilometres inland, and channel ice flow over considerable distances (Supplementary Information).

Particularly revealing, the three main branches of Upernavik Isstrøm (Fig. 1a), in West Greenland, coincide with three troughs with a submarine bed more than 80 km inland of their present termini, and for the southern arm more than 140 km. Previous mappings identify no trough (B2001, ref. 7), or reveal a glacier below sea level for 25 km (B2013, ref. 16), with large deviations (200 m) in bed elevation due to interpolation artefacts (Fig. 2). Farther north, near Hayes Gletscher, several unnamed glaciers share a common trough that is 15 km wide, 2 km deep and grounded below sea level for more than 120 km (Fig. 1b). Many glaciers of the northwest coast are grounded several hundred metres below sea level at their termini and remain so for 10–50 km inland. This contrasts with existing bed maps that indicate ice fronts grounded at sea level, not in contact with the ocean (Supplementary Information). Up north, Humboldt Gletscher is submarine 140 km inland of its terminus, and Petermann Gletscher (Fig. 1c) is underlaid by a submarine channel that connects to the ice-sheet interior, except for a narrow passage above sea level[21].

Few ice-covered, submarine valleys exist in the northernmost sector of Greenland. In the northeast, two large troughs more than 100 km long and 10 km wide host Academy Gletscher and Hagen Bræ (Fig. 1d). In central East Greenland, the bed is generally more than 1,000 m above sea level, so the glacial troughs in that sector are deeper and narrower than elsewhere in Greenland, but they do not extend far below sea level and far inland. We attribute this to the presence of a more resistant bedrock and the presence of a colder-based ice sheet[22]. Among them, Daugaard-Jensen Glacier (Fig. 1e) is grounded below sea level for 70 km, before its bed rises quickly above sea level over a broad plateau that would prevent any sort of rapid glacier retreat. Ice thickness is shallow on the

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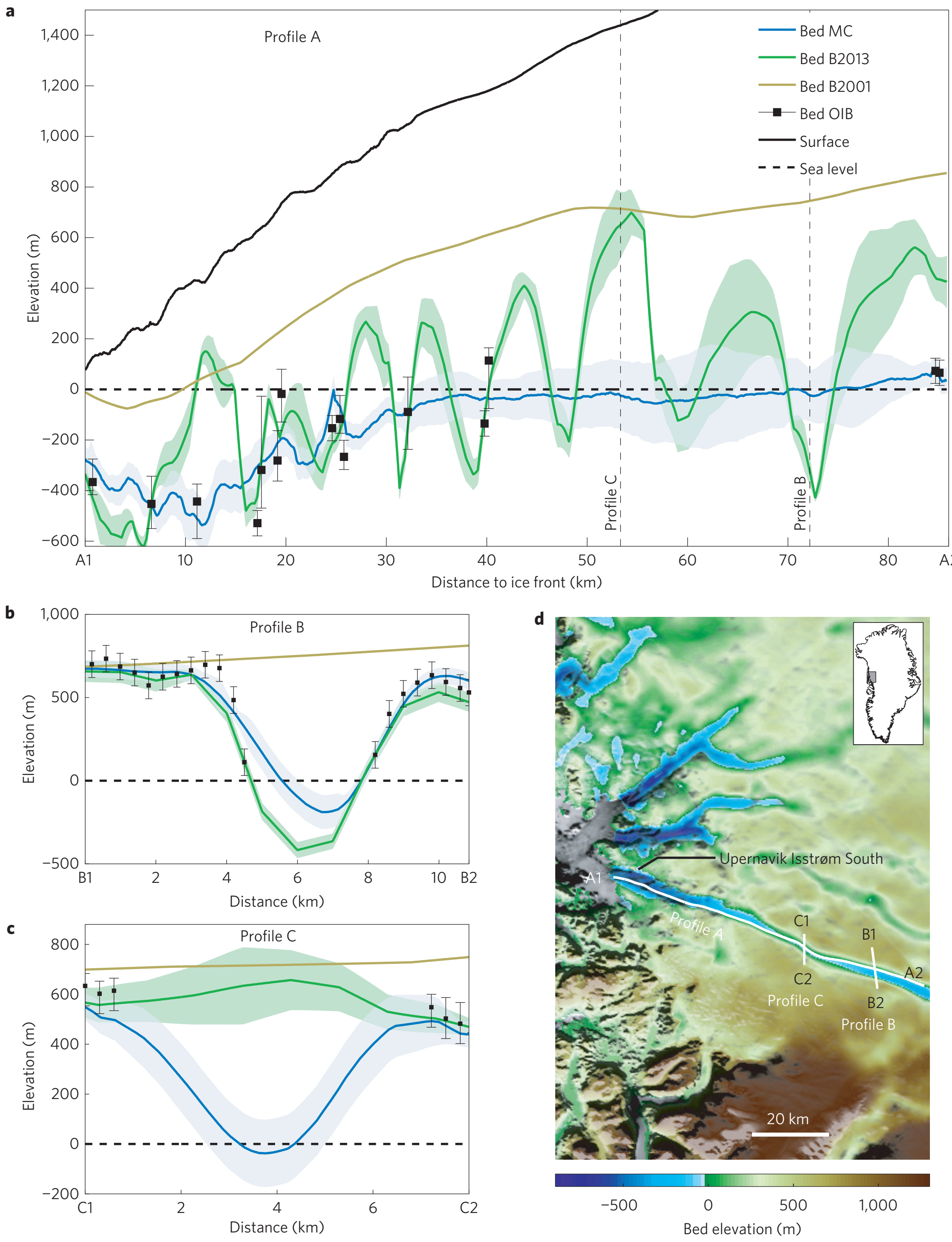

Figure 2 | Bed elevation of Upernavik Isstrøm South, West Greenland. Profiles A (**a**), B (**b**) and C (**c**), with their locations given in **d**, show the surface elevation in black, reference sea level in dashed black, bed topography B2001 from ref. 7 in brown, B2013 from ref. 16 and associated error in green, the mass conservation topography and associated error (2σ) in blue, and OIB bed elevation derived from radar tracks as black squares with error bars. **d**, Locations of the profiles A, B and C are shown as white lines, with a bed topography colour-coded between −900 and +1,300 m, overlaid on a radar mosaic of Greenland. Profiles B and C coincide with OIB flight lines.

Geikie Plateau, but an unknown deep, wide valley beneath Kong Christian IV Gletscher connects across the Geikie Peninsula with the ice-sheet interior. Farther south, Kangerlussuaq (Fig. 1f) and Helheimgletscher coincide with bed troughs 500 m deep and 80 km long that rise above sea level inland, and hence may not be conducive to ice-sheet drawdown. Between these large basins, two unknown submarine glacial valleys hosting fast ice streams drain Hutchinson Plateau towards Deception Island.

Bed mapping is less complete and more challenging in the south because radar-derived ice thickness data is sparse in warm-ice regions and data gaps exist in the ice velocity map. We generally detect submarine valleys in these glacial fjords, but the beds rise quickly above sea level inland (Supplementary Table 1). Few glaciers extend below sea level in the central south and southwest, except Ukaasorsuaq, Kangiata Nunaata Sermia and Narsap Sermia (Supplementary Information). Farther north, Jakobshavn Isbræ flows down one of the deepest and narrowest trenches in Greenland, with a bed several hundreds of metres deeper than in previous reconstructions[13].

The presence of thicker ice and deeper valleys along Greenland's periphery has great implications for our understanding and the modelling of glacier evolution. The depth of the glacier bed below sea level determines the potential for ice to be in contact with subsurface oceanic heat, typically 300–400 m below the surface, and whether this oceanic heat can follow the glacier inland during its retreat. Ice–ocean interactions are a major control on the evolution of Greenland glaciers[23] and the enhanced intrusion of warm water of sub-tropical origin (Atlantic water) in the glacial fjords is considered to be a leading explanation for the recent acceleration[24]. It has however been suggested that the current acceleration and retreat of these marine-terminating glaciers will decrease in the near future, as the ice sheet will lose contact with the ocean waters because the bed elevation of these glaciers rises above sea level within tens of kilometres of the coast[2,25,26]. Our results show that the submarine bed channels are more widespread, deeper and extend significantly farther inland than previously thought. In comparison with two existing maps of bed topography: B2001 (ref. 7) and B2013 (ref. 16), the 107 marine-terminating glaciers are underlaid by fjords that extend on average 67 km below sea level inland, which is 50% longer than for B2013 (Supplementary Table 1) and 300% than for B2001. If these 107 glaciers were to retreat at an average rate of 110 m yr^{-1} in the coming century, as they have between 2000 and 2012[26], only 30 of them would disconnect from the ocean by the end of the century. We report 123 marine-terminating glaciers versus 12 in B2001 and 102 in B2013. More important, out of these 123 marine-terminating glaciers, 60 drain 88% of the ice sheet in area and are grounded below 300 m depth at their termini, meaning they are deep enough to interact with subsurface warm Atlantic waters and undergo massive rates of subaqueous melting[23].

Most recent numerical modelling of the evolution of Greenland in a warmer climate employs B2001 thickness and bed data or some improved version that adds new kriging products from three large glacier systems: Jakobshavn Isbræ, Helheim and Kangerlussuaq Gletschers[1–3,18]. Numerical models for the ice sheet therefore employ a shallow, smoothed bed topography that restrains the outflow of glacier ice into the ocean and suppresses contact with the ocean waters in most fjords. Unsurprisingly, the numerical models tend to predict thickening of the ice sheet along the periphery, and a weak sensitivity to ocean thermal forcing, which are both in contrast to recent observations.

The presence of deep, widespread submarine glacial valleys around Greenland implies that Greenland outlet glaciers, and the Greenland ice sheet as a whole, are more vulnerable to ocean forcing than previously thought and will retreat faster and farther inland than anticipated because most of these bed troughs are well eroded with very few areas of higher ground that could halt a glacier retreat. We anticipate that these results will have a profound and transforming impact on model simulations of ice-sheet evolution in Greenland and reveal a more pervasive influence of ocean thermal forcing on these glaciers, which is more consistent with the past two decades of satellite observations.

Methods

The MC method[5,15] solves the mass conservation equation to derive ice thickness, while at the same time minimizing departure from the original radar-derived ice thickness data. We rely here on the finite element method using unstructured triangle meshes (Supplementary Information). To apply the MC method, we use OIB radar-derived thickness data, posted at 15 m, with a vertical precision[27] of 30 m (https://data.cresis.ku.edu/data/rds/) and ice velocity measurements derived from satellite radar data collected during 2008–2009 by the Japanese Advanced Land Observing System (ALOS) PALSAR, the Canadian RADARSAT-1 SAR, the German TerraSAR-X (ref. 25), and the European Envisat Advanced SAR (ASAR), posted at 150 m, with errors of 10 m yr^{-1} in speed and 1.5° in flow direction[8] (http://www.ess.uci.edu/group/erignot/node/1535). Ancillary input products include surface mass balance (SMB) averaged for the years 1961–1990[28] at 11-km posting with a precision between 7% and and 20% in the ablation zone (dataset available on request to the authors), and ice thickening rates combining satellite and airborne altimetry for the years 2003–2008, at a 1/10th of a degree posting, with a precision[29] of 20 cm yr^{-1} (http://data.eol.ucar.edu/codiac/dss/id=106.395). The algorithm neglects ice motion by internal shear, which is an excellent approximation[5,15] for fast-flowing glaciers (>100 m yr^{-1}). The optimization procedure is not applied to slow-moving sectors, for which conventional kriging is used. In a trial setting with unusually dense radar sounding coverage, we report errors in the MC-inferred thickness of 36 m, only slightly higher than that of the original data[15]. In areas less well constrained by radar-derived thickness data, or constrained by only one track of data, for example, in south Greenland, errors may exceed 50 m (ref. 15) (Supplementary Information). Consistent thickness estimates are obtained using ice velocities from different years, and in the presence of errors in the SMB or thickening rates (Supplementary Information), which suggests that our method is robust. The bed topography is derived by subtracting the ice thickness from the Greenland Mapping Project (GIMP; ref. 14) Digital Elevation Model (http://bprc.osu.edu/GDG/gimpdem.php). The bed topography map will be available as an Operation IceBridge Earth Science Data Set at the National Snow and Ice Data Center (NSIDC).

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Author contributions

M.M. developed the algorithm and led the calculations. H.S. assisted in implementing the algorithm. J.M. provided velocity mapping. All authors contributed to the writing of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.M.

Competing financial interests

The authors declare no competing financial interests.