from most other Solar System bodies (Fig. 1). This implied that the Sun itself is ^{16}O-rich, just like the calcium–aluminium-rich inclusions (CAIs) that are found in meteorites and are believed to be among the oldest solid bodies in the Solar System. Now, Ireland *et al.*[1] report results from a contemporary lunar soil that support the opposite conclusion.

The main difference between the two studies is the choice of sample. Hashizume and Chaussidon[2] used a sample of ancient lunar regolith that they had previously shown contained carbon enriched in ^{13}C (ref. 6) and nitrogen depleted in ^{15}N (ref. 7), results they ascribed to the effect of the solar wind. Their metal grains contained a thick oxide layer that compromised the normal solar-wind implantation profile, but the authors identified ^{16}O-rich oxygen they found inside the grains as so-called solar energetic particles. These particles travel at much higher speeds than normal solar-wind particles, and are therefore much more deeply embedded in the grains.

Ireland and colleagues[1] used a sample of lunar soil only recently exposed to the solar wind, but which had one of the highest exposures known. Their metal grains had only a very thin oxide layer, and the ^{16}O-poor oxygen was found at a depth consistent with normal implanted solar wind. The two studies[1,2] thus measured solar particles of different ages and, apparently, from different energy regimes. Yet even taking these facts into account, such divergent results are hard to understand.

Processes within the Sun, and those that accelerate solar-wind and solar energetic particles away from its surface, would be expected to affect isotopic composition in a mass-dependent manner. Thus, samples would simply move up or down a line of slope 0.5 on the three-isotope plot. To move away from such a line, either oxygen of a different composition must be added or a process that is mass independent must be invoked. Although the outer layer of the Sun could have changed through the addition of new material over two billion years, there is no known reservoir of material in the Solar System that has a composition extreme enough or a mass great enough to shift the composition of this layer by the required amount.

A process called self-shielding can also alter oxygen isotopic composition. When certain compounds such as carbon monoxide are exposed to intense ultraviolet radiation, molecules containing the highly abundant ^{16}O can exhaust the supply of photons with the correct energy to break them up, although there are still plenty of photons that can disrupt molecules containing ^{17}O and ^{18}O. A reservoir of oxygen with a composition different from the starting carbon monoxide can be created if the released oxygen becomes trapped in a different molecule, such as water[5]. But there is no obvious way to apply this mechanism to solar-wind or solar energetic particles.

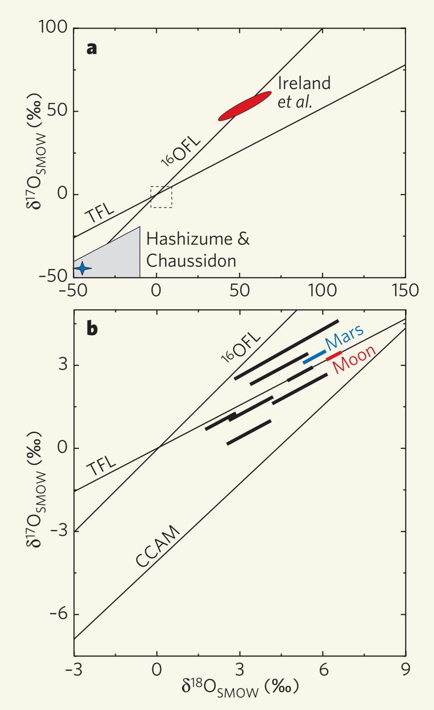

Figure 1 | Oxygen in the Solar System. The quantities $\delta^{17}O$ and $\delta^{18}O$ give deviations in the ratios $^{17}O/^{16}O$ and $^{18}O/^{16}O$ relative to the same ratios in standard mean ocean water (SMOW), with $\delta^{17}O = [(^{17}O/^{16}O)_{sample}/(^{17}O/^{16}O)_{SMOW} - 1] \times 1{,}000$, and similarly for $\delta^{18}O$. **a**, Solar System material lies within the small box at the intersection of two lines: the terrestrial mass fractionation line, TFL, with slope 0.5 and along which all samples from Earth lie; and the ^{16}O fractionation line, ^{16}OFL, with gradient 1. Samples with enhanced or depleted ^{16}O content compared with the SMOW value lie farther up or down the ^{16}OFL line, respectively. The star represents the ratios found in Ca–Al-rich inclusions (CAIs) from meteorites. Hashizume and Chaussidon's results from lunar soils[2] lie within the grey area; Ireland and colleagues' new findings[1] are in the red disc. **b**, An expansion of the intersect area, showing the lines on which the oxygen isotopic compositions for samples from Mars, the Moon and various meteorite parent bodies sit. The line CCAM refers to an array of measurements of minerals in CAIs.

We are therefore left with an intriguing dilemma. The data both of Hashizume and Chaussidon[2] and of Ireland and colleagues[1] are good. Their results cannot, however, be explained within our current understanding of oxygen isotopes and the structure of the Sun. More data should help: a major goal of NASA's Genesis mission, launched in 2001 to capture the solar wind, was to determine the oxygen isotopic composition of the Sun. But the difficulty inherent in measuring oxygen in the Genesis collectors, and the complications introduced when the spacecraft crashed into the Utah desert on its return to Earth in 2004, mean that it will be some time before we have further data. Depending on the results, some new ideas might be required. ■

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ARCHAEOLOGY

Failure and how to avoid it

Kathleen D. Morrison

Nothing lasts for ever, not least human civilizations. There are many reasons why societies stand or fall, and these lessons from the past require investigation at various places and on various timescales.

Archaeology, it seems, really is a matter of life and death — this was the theme to emerge from a meeting* convened to address the question of what makes societies more likely to collapse or to achieve long-term sustainability. Just as we do today, our ancestors faced problems of resource depletion, environmental degradation, political instability, demographic pressure and social upheaval. And, as today, success in dealing with these challenges was never assured.

Consider the following contrasts. The islands of eastern Polynesia were all settled within a few centuries of one another by people sharing the same ancestral culture. Yet whereas some islands, such as Tahiti, have sustained human populations for centuries, others, such as Easter Island (Rapa Nui), supported populous and complex societies for

**How Societies Chose to Fail or Succeed*, Global Institute of Sustainability Workshop, Arizona State University, Tempe, Arizona, USA, 31 January to 2 February 2006.

Figure 1 | Societal collapse: the case of the Classic Maya. The complex urban way of life of the Maya ended abruptly between the ninth and tenth centuries AD. Monumental construction for the élite (such as Temple 1 at Tikal, left) ceased entirely. Political collapse was accompanied by large-scale depopulation, indicating problems at all levels of society. Archaeological and palaeoenvironmental data indicate environmental degradation caused by intensive agriculture (upper right, raised and ditched fields from the Upper Booth's River in Belize). In contrast, the great city of Teotihuacan in central Mexico (lower right, Pyramid of the Sun and the Avenue of the Dead in the city centre) lasted from about 100 BC to AD 650, with continued intensive occupation of the region to the present. In each case, both social strategies and environmental factors influenced the chances of long-term success.

only a short time before experiencing profound demographic and social disruption.

Completely isolated since its initial colonization, variously dated between about AD 750 and 1200[1,2], this scrap of land came to the notice of the world with the visit of the Dutch explorer Jacob Roggeveen on Easter Sunday, 1722. Roggeveen marvelled not only at the more than 200 massive stone statues, the Moai, which ring the coast, but also at the barrenness of the landscape and the destitution of its small population. The rich soils of Easter Island, oddly enough, supported a depauperate vegetation virtually devoid of woody plants.

That Easter Island had once supported a much larger population with a complex political structure was clear from the archaeological record. But it took a combination of archaeological and palaeoenvironmental data (pollen, microscopic charcoal and faunal analysis) to reveal the extent to which the island's degraded landscape was a product of human action. Once covered by subtropical forests dominated by a now-extinct species of large palm[3,4], the island environment was ravaged by intensive human exploitation. With the destruction of plants for canoe-building, offshore food resources such as the marine mammals exploited early in the island's human history receded from reach, as did any chance of mobility as an option for addressing the mismatch between resources and needs.

Although ecological constraints certainly played a role in the variable success of human populations on Pacific islands (B. Rolett, Univ. Hawaii), cultural practices were clearly also crucial. Longer-term sustainability involved agricultural systems and levels of resource extraction compatible with local conditions.

Not all anthropogenic environmental change has led to cultural collapse, as both the contrasts between Pacific islands and the evidence from more complex continental contexts shows. One such comparison is between the long-term occupation of the Basin of Mexico and the well-studied collapse of the Classic-period Maya (Fig. 1). The Maya, a complex urban society organized into a series of competitive city states, abruptly ceased building monumental structures around the ninth century AD. Large parts of the Maya homeland were depopulated, although others continued to thrive. Many factors — including environmental degradation, population expansion, warfare and a decline in the ideology of kingship — seem to have been at issue in the collapse (D. Webster, Penn. State Univ.). Not far away, however, in central Mexico, the city of Teotihuacan managed to maintain a large population, perhaps as many as 100,000 people, for more than 400 years (G. Cowgill, Arizona State Univ.). The area has continued to support a large population to this day.

The experiences of past societies may be thought of as social and ecological 'experiments' (C. Redman, Arizona State Univ.). In each case, past conditions, responses to change (real or perceived) and outcomes of behaviour constitute data for broader comparisons. Defining cases requires more precise definitions, drawing distinctions between restorations of continuity, societal transformations, failures or 'mini-collapses' such as dynastic transitions, and collapse proper (Redman). Considerations of spatial and temporal scale are essential, not least in defining sustainability. The historical record represents the cumulative outcome of multiple processes (S. van der Leeuw, Arizona State Univ.), so explanations must integrate processes and contingent events operating at different scales.

Several factors seem to have determined whether societies failed, collapsed, or experienced either episodic change or 'radical continuity'. On the one hand, environmental changes, natural or self-inflicted, caused or assisted many cases of collapse and failure (J. Betancourt, Univ. Arizona). Other factors include rates of demographic change (Webster), the degree to which élites were isolated (and insulated) from social problems, the strength of communication across hierarchies (S. Schroeder, Univ. Wisconsin), levels of investment in infrastructure, and the ability to balance commitment to cultural values with the flexibility required to manage uncertainty (J. Diamond, UCLA; M. Nelson, K. Spielmann, Arizona State Univ.).

In the past, many societies with fewer vulnerabilities than today's Western societies have failed, whereas others with more vulnerabilities have succeeded (B. Nelson, Arizona State Univ.). The long archaeological record of human history constitutes the best and, for most of our history, the only source of data about the long-term consequences of human choices. One of the values of archaeological research is that it offers a rich source of data on human actions and their consequences — data that may someday play the same kind of role in understanding present challenges that palaeoecology now does in climate modelling. By identifying the differences, as well as the similarities, between past and present societies, archaeology can publicize environmental and social risks and vulnerabilities while underscoring an increasingly wide range of technical and cultural solutions (Betancourt).

What lessons does current archaeological research have for policy-makers? For one, it is clear that large-scale environmental degradation is almost always a factor in social collapse. Awareness of ecological inflexion points, beyond which recovery is no longer possible, may make the difference between success and failure. Total collapse of a civilization may be rare, but cultural transformations are not only common but perhaps also necessary. For example, the long-term occupation of parts of south Asia may have been made possible by a willingness to experiment with new social forms and technological strategies, including radical changes in agriculture and cuisine. In today's globally connected world, failures tend to have ramifications well beyond local contexts, making the lessons of the past perhaps even more relevant. ■

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FLUID DYNAMICS

The rough with the smooth

Kwing-So Choi

Those who go with the flow assert that rough surfaces cause turbulence in fluids passing over them. The claim that, under certain conditions, the opposite is possible disturbs that cherished belief.

Have you noticed how slick the exteriors of cars have become lately? Side mirrors are aerodynamically shaped; windows are an integral part of the doors; no parts hang out over the side of the body. Even windscreen wipers can be retracted when not in use. A smooth body is not only better looking; it can reduce aerodynamic drag, and thus makes a car faster and more fuel-efficient — or so we are led to believe. In fact, this prevailing wisdom may not be true: Fransson *et al.*[1] report in *Physical Review Letters* that surface bumps are actually useful for reducing drag. So what's going on?

To get to the bottom of this matter, we must look at the evolution of fluid flows over a solid surface. Initially, these flows are silky smooth and move together; they are 'laminar'. Soon, however, the inherent instability of a laminar flow leads to its becoming random and chaotic, or 'turbulent'. Turbulent flow is usually associated with characteristics such as strong mixing of the fluid and high energy loss through dissipation. The drag that cars experience is therefore greater when the surrounding flow is turbulent: if a laminar flow can be maintained, the frictional drag acting on the car is much less.

Fransson and colleagues[1] conducted experiments under controlled conditions in a wind tunnel, and were able to maintain laminar flow along a wall for longer by deliberately making its surface rough. We naively expect that surface roughness will create disturbances that lead to turbulent flow, so the result is, on the face of it, puzzling. But the authors were able to show that, by carefully controlling the disturbances created by the surface roughness, they could make the flow over a body surface more resistant to a certain type of instability, and so postpone the onset of turbulence until farther downstream (Fig. 1).

The authors used a flat wall, to which uniformly distributed 'roughness' elements were attached that produced steady, corkscrew-like disturbances in the flow, called streaks. Their experimental results confirm simulations showing[2] that a moderate strength of streaks can indeed stabilize the laminar flow. Although the size and shape of roughness elements are important in this experiment, the strength of the disturbance they create in the flow is also crucial. If this is too strong, a more deadly instability kicks in and the flow quickly becomes turbulent[3].

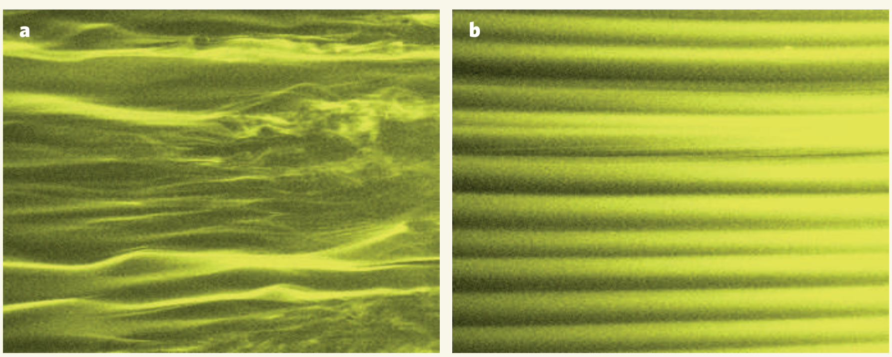

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Figure 1 | Flow patterns visualized by smoke. a, Laminar flow goes through the transition to turbulence without surface roughness. **b,** Fransson *et al.*[1] maintain laminar flow for longer with a rough surface that creates regular disturbances.

Using surface roughness to reduce friction drag is, in the case of turbulent flow, not new. Randomized, V-shaped roughness elements are known to reduce friction drag[4] in such flows, as are sand grains attached to a surface[5]. Cross-flow variation — a disturbance in velocity that occurs at right angles to the main flow — is also known to be caused by regular roughness elements. Its effect on turbulent flow has been studied theoretically[6] by solving the equations governing fluid flows directly by computer.

In these cases, the key to drag reduction is efficient modification of organized structures of various shapes that have been identified as supplying most of the energy in turbulent flows. It has been argued that randomized roughness elements destroy such structures[4], whereas cross-flow variation stabilizes a flow[6], thus preventing the structures' reproduction. A regular pattern of roughness elements that introduces such a cross-flow variation to a laminar flow is central to Fransson and colleagues' study[1]. Their success in reducing drag reinforces the idea that organized structures in turbulent flows are the remnants of laminar flow structures after they have undergone the transition to turbulence.

Several investigations have sought to repeat physical and numerical experiments by artificially introducing disturbances into the flow, but only a few[7] have succeeded. This implies that such results might be sensitive to small variations in geometric and flow parameters. So how robust is the flow-control strategy proposed by Fransson and colleagues?

It is fair to say that, as the shape of the roughness elements is critically important in stabilizing laminar flow, totally different flow patterns might emerge even when their shape is changed only slightly. Applying the technique to high-speed flows might also present a problem, as the streaks will become unsteady at higher speed. Roughness elements will introduce additional drag as they disturb the flow, so any reduction in friction drag by roughness elements must compensate for this if a strategy is to have practical value.

The prize for overcoming such problems, and recognizing that smooth is not everything, is great. Its value lies in the ability to design and build fuel-efficient airplanes, quieter submarines and faster cars — both more easily and more cheaply. ■

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